

Hydrological Aspects of Drought in Scotland  
and Their  
Implications for Water Resource Management.

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## PREFACE

This Thesis is presented in fulfillment of the requirements of the degree of Doctor of Philosophy of the University of Edinburgh.

The research undertaken for this Thesis was carried out over the period 1978 to 1981, and was supported by a grant from the Natural Environment Research Council. I certify that the work reported in this Thesis, except where stated otherwise, is the result of my own original research.

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The investigative nature of this Thesis has required that large amounts of data be made available. The various sources of information collected for this Thesis are rather numerous, and many organisations deserve grateful thanks for their cooperation in this matter.

The Meteorological Office has kindly made available all the hydrometeorological data analysed in this Thesis. Special thanks are due to all River Purification Boards in Scotland, namely, the Clyde, Forth, Highland, North-East, Solway, Tay and Tweed, for the provision of hydrological data, especially that which is not normally published or reported. Also, the cooperation of the water management departments of the Borders, Fife, Grampian, Highland, Lothian and Tayside Regional Councils is gratefully acknowledged. Lothian Region Water Supply Services deserve special mention, for allowing access to archived historical records.

Several individuals have also been instrumental in the development and completion of this Thesis. Firstly, I would like to thank my supervisor, Dr. D. C. Ledger, for his help and guidance throughout the course of study. In addition, Mrs. Elisabeth Grosse deserves thanks for her speedy and efficient typing service, as does my wife, Mary-Helen, for her support during the latter stages of the preparation of this thesis.

# ABSTRACT OF THESIS (Regulation 6.9)

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Initially, this thesis considers the general nature of "drought", and in particular that of the drought affecting Scotland during the period 1971-76. The eastern part of the country is identified as that suffering the longest and severest drought spells over this period, by way of detailed investigation of various hydrometeorological and hydrological measures of drought. Attention is focussed on the hydrological aspects of drought in Scotland by way of two special studies. The first involves the derivation and analysis of a 92-year long record of annual run-off for a reservoir catchment in south-east Scotland. The second is concerned with the collection and collation of all available low flow yields in the East of Scotland, and the subsequent development of detailed maps depicting 1 and 5 percentile run-off levels. This exercise reveals the large degree of variation in such yields throughout the country.

The effects of the hydrological abnormalities of the 1971-76 period are considered for two main areas of water management, namely, public water supply provision, and waste water disposal. The relatively localised drought impacts associated with the latter are described, to varying degrees of detail, in a series of case studies. Impacts concerning the former are analysed from a national viewpoint, with particular regard paid to the wide range of drought impacts and management problems associated with water supply reservoirs.

This is followed by an appraisal of the existing policies governing the planning and management of water supply systems (especially reservoir ones) in Scotland, in relation to the hazard of drought. Relevant shortcomings are recognised, and techniques for overcoming them are presented. In effect, a new systematic and thorough approach to optimal yield estimation and drought management of reservoir water supply systems is put forward, by way of a case study.

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SECTION 1  
INTRODUCTION



## 1.1 INTRODUCTION

Drought is an inescapable fact of life. Life is ultimately dependent on water, and consequently the hazard of drought poses a threat everywhere on the Earth's surface where some biological activity exists.

Human perception of drought hazard can be limited by the fact that very long periods, often greater than a human lifespan, can separate notable events. However, as Tannehill (1947) appropriately, although somewhat dramatically, reminds us,

"(drought) creeps upon us gradually, almost mysteriously, but its consequences are a terrible reality".

All the above observations are generally supported by historical evidence going back to biblical times. According to Brooks and Glasspoole (1928), scant records of droughts in Britain date from the year 298 A.D., and in Scotland in particular, from 480 A.D.

Droughts in the more recent past have generally been well documented, along with the wide range of related impacts in different regions of the world. For example, Hoyt (1936) reviews the effects of drought in the early 1930's in the United States, on such diverse aspects as, agriculture, domestic water supply, public health, navigation, recreation, and wildlife. Foley (1957) similarly considers droughts over a 100-year period in Australia.

More recently, drought has been a subject of great concern in Britain, because of the events of 1975/76

affecting parts of England and Wales. The numerous publications describing specific aspects of this drought include those of Perry (1976) and Murray (1977) who cover the relevant meteorological and hydrometeorological matters respectively. The effects on agriculture are reported by Roy et al (1978), and hydrological reviews are provided by the Central Water Planning Unit (1977) and Beran and Kitson (1977). Analyses of a more comprehensive nature are presented by the Royal Society (1978) and Doornkamp et al (1980).

No previous drought affecting the U.K. has ever been studied in such detail, as seems appropriate since the 1975/76 event was such that Meaden (1976) considers it to be the driest since that of 1252/53 A.D.

Such climatic abnormalities were globally widespread in the early and mid 1970's. The 1971-73 drought in West Africa which affected the desert margin region of the Sahel (Davey, 1974 and Landsberg, 1975) was probably the most severe in terms of impact. However, the year 1972 in particular produced many extremes of climate. Hare (1977) lists the following events;

- (i) the coldest year on record in much of North America;
- (ii) drought and failure of snow cover in the Soviet Union;
- (iii) drought in Australia;
- (iv) heavy ice blocking marginal Arctic Seas;
- (v) crop failures in many counties and severe price inflation on agricultural markets.

Further to this, Young (1976) mentions a "serious drought" suffered in Japan in 1972. Perhaps less well documented is the fact that this year was at the crux of the most severe drought period to affect much of Scotland for a very long time.

It is this drought event which has provided both and inspiration and the majority of the subject matter for this thesis.

## 1.2 REASONS FOR THE STUDY

### 1.2.1 General

The need for thorough and systematic assessments of climatically-induced crises is recognised by many commentators, such as Tickell (1977) and Hare (1977). The proliferation and severity of recent drought events have reinforced the urgency of the cause to assimilate information which could provide for the alleviation of the effects of future droughts. As a direct result of the water shortages, particularly those in Africa and Asia, occurring in the early 1970's, the World Meteorological Organisation (1975b) decided to give "greatly increased attention" to the subject of drought.

Apart from the obvious necessity of acquiring a thorough understanding of possible fluctuations in a given area's climate, further concern is evoked by the view of

Tase (1976). Along with others, he considers that the continuation of the pressures of both increasing populations and increasing per capita water demand, will make drought problems much more serious in the future. Any water shortages associated with such escalating requirements would be most problematic where limited supplies are available.

Also, there is the distinct possibility that there will be more at stake to be affected by droughts in the future in that both the population and the potential economic losses in vulnerable areas may be higher than at present.

#### 1.2.2 Specific

In the midst of other droughts of the 1970's, especially those in the Sahel and in England and Wales, perhaps the events occurring in Scotland over this period have been somewhat neglected, and thus merit a comprehensive study. Further reason for giving attention to the subject of drought in Scotland is provided by the fact that over the past thirty years, three major periods of drought have affected the country, namely those of 1955, 1959 and the 1970's. The matter as to whether the relative neglect paid to such events, with specific regard to the last one, has been due to their insignificance or otherwise, will be investigated in this study. In addition, in view of their debatable significance, the matter as to whether the term "drought" actually applies to such occurrences deserves some consideration.



What reports and studies are available, give an indication of the unique and important nature of the meteorological and hydrological events affecting Scotland in the period 1971-76. For instance, the Meteorological Office (1980) report that Scotland, as a whole, received only 81% of the 1941-70 (the current standard meteorological reference period) average precipitation in the year 1972. The geographical variation was such that, whereas the extreme south-west of the country experienced above average annual precipitation, much of the eastern part of Scotland received less than 70% of the 1941-70 average. By all accounts, this latter figure represents a considerably rare event. For instance, Ledger and Thom (1977) investigated the two hundred year old rainfall record for Blackford Hill in Edinburgh, for which 1972 (70% of the 1941-70 average) and 1973 (68% of the 1941-70 average) are in the driest 5% of all annual events. More significantly, the combined two-year precipitation is by far, the lowest on record. A similar analysis of potential moisture deficits by the above authors has revealed that the continuous event during the period 1972-74 was the most severe over two hundred years in Edinburgh.

Use of this same rainfall record was made by Thom and Ledger (1976) to derive an annual series of "potential excess winter rain" values, which they showed could successfully be used as an index of annual run-off. This study further indicated the unique hydrometeorological nature of the year of 1972 by indentifying it as the one of lowest potential excess winter rain for at least two hundred years in the Edinburgh area.

Although based on much shorter periods of data, actual measurements of run-off in the East of Scotland provide further supportive evidence for the above contention. River flows, over most durations from the instantaneous to those of several years, were the lowest-ever recorded in this part of the country. For example, on the R. Dee at Woodend in the Grampian Region, 1973 had the least run-off of all years since records commenced in 1930 (North East River Purification Board, 1980). In addition, a lowest-ever instantaneous flow occurred in 1972, only to be displaced from this standing by the extreme events of 1976.

Such low flows were associated with diverse ecological and economic problems. For example, they were blamed for reduced salmon catches on the R. Tweed (Berwickshire News and East Lothian Advertiser, 25.9.73) and on the R. Tay (Dundee Courier and Advertiser, 21.8.76). Both of these rivers are in the top three of the largest, and the most important salmon rivers in Scotland.

A most notable consequence of the low river flows was that many water supply reservoirs reached very low levels for long periods. For example, Fife's reservoired supplies were at maximum capacity for only one month (February, 1975) during the entire 1971-76 period. The response of the relevant water authority, along with several others was to apply restrictions on public water consumption. For instance, the Fife Free Press of 4.9.75 reported that despite the securing of emergency water supplies, the

Fife and Kinross Water Board were imposing a ban on the use of hosepipes for the fifth consecutive year in their area.

The following front page headlines taken from regional newspapers give an indication of the widespread nature of the difficulties experienced by water authorities, and the impacts suffered by public water supply consumers during the drought period.

"Water lack in North-East never so bad."

(Aberdeen Press and Journal, 12.9.72)

"Urgent Save Water Appeal - Cuts in the Public Supply are Threatened."

(Dalkeith Advertiser, 1.2.73)

"Save Water Campaign Stepped Up."

(Dalkeith Advertiser, 21.6.73)

"Critical Water Situation."

(St. Andrews Citizen, 13.10.73)

"Further Pleas for Water Restraint."

(Northern Scot, 18.9.76)

Whilst such reports reveal the considerable level of concern apparent during the 1971-76 period, it is notable that at no point during or after this time was a comprehensive drought study published. The two most obvious reasons providing an explanation for this situation are that;

(i) the events were not as severe as the press reports would indicate, and that a national review of the drought period was not necessary; or (ii) no official national body, which could be expected to conduct such a study, existed or was formed.

Preliminary contact with Water Board officials, and other relevant parties, such as River Purification Boards, carried out in the initial stages of this study, has indicated the latter reason to be the more likely. It is considered that these findings provide sufficient justification for the comprehensive documentation and investigation of the drought over the 1971-76 period in Scotland, which is presented in this thesis.

### 1.3 STRUCTURE OF THE THESIS

Once a suitable and applicable definition of drought has been determined, Section Two of this thesis is concerned with the nature of the hydrometeorological and hydrological events of the identified drought period, in terms of both their areal and temporal distributions. In addition to consideration of such measures as deviations from average precipitation values, use of what long term records are available is made, to allow the above events to be put into their historical perspective. In this study, this situation applies in particular to run-off events, for which there is a dearth of readily available long term data. As well as this paucity of run-off data in the dimension of time, another, on an areal basis is also apparent. This is because actual records of river discharge typically apply only to specific gauged catchments. Therefore, there are instances where insufficient quantities



of such sample data are available to allow rigorous areal comparisons and assessments of drought severity to be made. It is therefore the intention here to attempt to employ some method of estimating flows, and in particular low ones, from catchments which are not normally gauged.

Section Three considers the effects of water shortages associated with the previously defined hydrological conditions. The relevant impacts on environmental requirements and on public water consumers are investigated for each of the two separate spheres of waste water disposal and water supply provision.

Following the above assessment of water shortages and their impacts, the Fourth Section appraises the suitability of the existing policies governing the planning and management of water resources (especially water supply reservoirs) in Scotland, in relation to drought events such as those of the 1970's.

In the penultimate Section, of number Five, a model for optimising the planning and management of water supply reservoirs in relation to drought is presented, in an attempt to provide a more systematic and thorough method of managing this largely unpredictable and inescapable hazard.

Finally, Section Six contains the general conclusions reached in the course of the work presented in this thesis.

SECTION 2

THE HYDROMETEOROLOGICAL AND  
HYDROLOGICAL EVENTS OF THE  
1971-76 PERIOD

## 2.1 A DEFINITION OF DROUGHT

As indicated in the Introduction, a general definition of drought is necessary to clarify what is meant by the term at this stage in the study. Although several authors have suggested various general definitions of drought, many of these tend to be rather specific in that they relate to one particular region, and one viewpoint. For example, Russel (1896) is credited by Foley (1957) with one of the earlier definitions, ie.

"a period of months or years during which little rain falls and the country gets burnt up, grass and water disappear, crops become worthless and sheep and cattle die."

Although more appropriate than many of its contemporaries, this rather long-winded description refers specifically to the Australian agricultural situation. Indeed, this tendency for specialised definitions led Subrahmanyam (1967) to conclude that a completely satisfactory or universal definition was unavailable and "even almost impossible to find".

Despite this, Maher (1968) suggested,

"a severe and prolonged water shortage" as a suitable general definition. However, this is of limited use in that it implies a time requirement, it does not mention unusual weather, and it includes only consideration of water supply, and not demand. This last

shortcoming was recognised by Gibbs (1975), and his contention that any definition which ignored water demand was inadequate led to his suggestion of;

"lack of sufficient water to meet requirements", This provides a more comprehensive definition of drought, but despite the added advantage of the omission of a duration factor and hence its being more universally appropriate, it still ignores the influence of any climatic variation on a drought-associated water shortage.

However, Huschke (1959) includes all the necessary ingredients by defining drought as;

"a period of abnormally dry weather sufficiently prolonged for lack of water to cause serious hydrological imbalance (ie. crop damage, water supply shortage)"

If the qualifying adjectives, ie. dry, prolonged and serious, which could possibly limit the application of this definition, are removed and Gibbs's conciseness is included, then possibly the most apt general definition can be derived ie.,

"a period of abnormal weather involving a lack of water to meet requirements"

This generalised, but universally applicable definition can be applied to different drought situations, in different regions, looked at from different points of view. For example; "abnormal weather" can include a lack of rain, or an increase in temperature or ventilation causing greater evaporation; the "water" can be in the atmosphere, on the ground, in the ground, in a river, in a lake or in a



reservoir; the "requirements" can be agricultural, ecological, economic, for industrial or domestic water supply, or for effluent disposal.

Extending this definition to its application to drought analysis, the meteorological interests can be measured in terms of their abnormality. All other aspects of drought can be assessed firstly by measuring the supply of water, and secondly by measuring demand, to allow the derivation of the degree to which requirements go unfilled.

Further ramifications of the above concept of drought are considered in Section 4, particularly those related to the matter as to what actually constitutes a drought in Scotland, or anywhere else in the world. However, there now follows a discussion on the methods available for assessing the meteorological matters and the primary aspects of "supply" (ie. those not influenced by artificial means) involved in a drought.

## 2.2 A CONSIDERATION OF MEASURES AND INDICES OF DROUGHT

Now that a satisfactory general definition of drought has been reached, there remains the problem of determining the most appropriate ways of measuring the climatic and hydrologic aspects of drought.

Yevjevich (1967) summarised the following measurable factors pertaining to hydrologic drought;

(i) severity; (ii) probability of recurrence; (iii) duration; (iv) areal extension; and (v) initiation (or termination).

The first, severity is arguably the most important feature since it can be taken to, at least partially, involve some of the others. The following four different sets of criteria are those available for the measurement of the general term of "drought severity".

A) Actual measures of climatic & hydrologic variables

In the case of rainfall, for example, actual values could be used as an index inversely proportional to the degree of drought. Thus, Thornthwaite (1947) identified areas of "permanent drought" and "seasonal drought". In the case of the former, as Palmer (1965) indicated, this classification is somewhat unnecessary, in that areas experiencing such conditions are already climatically classed as "arid" or "desert". The incidence of seasonal drought on the other hand, would occur as part of the normal climatic regime in areas having well-defined wet and dry seasons. Therefore, as this also does not involve "abnormal weather" in a given area, then such occurrences are not "drought" as defined previously.

B) Actual or relative durations from average values

This type of measure has been applied mostly to rainfall, but also to temperature and evaporation. Criteria

for the occurrence of drought vary widely, mostly according to the time span involved. For example, when considering short durations, Cole (1933) defined drought in the United States as a period of 15 days with zero rainfall. Around the same time, the British Rainfall Organisation (1936) used similar criteria to develop a classification of 3 levels of drought as follows:

absolute drought: at least 15 consecutive days, none of which received as much as 0.25mm.  
partial drought : at least 29 days during which mean rainfall does not exceed 0.25mm per day.  
dry spell : 15 consecutive days, none of which has received as much as 1mm.

Further criteria, arrived at in different parts of the world, concerning longer durations of drought also tend to be broadly similar. As the duration, increases, then the deviation from normal rainfall which is termed a "drought" tends to decrease.' For example, Glasspoole (1924) recommended the retention of the use of 80% of average rainfall over a period of 3 years as a criterion for assessing the reliability of water supply systems. In the United States, Bates (1935) based his assessment of drought on 75% of normal annual precipitation, and 60% of normal monthly precipitation, whilst in Australia, Baldwin-Wiseman (1941) designated an "engineer's drought" as a period of 3 or more months with a deficit of 50% from mean rainfall.

Apart from their specific application to one country, the approaches above are of limited use when it comes to

assessing drought severity. Firstly, those of a fixed short period, where zero or near zero rainfall is a criterion, allow no means of comparing the severities of different drought events. The others could allow some relative comparison for one location, but the rigidity of the specified time periods can reduce their usefulness.

This limitation was removed by Hoyt (1936) in his definition of drought in the United States as any period with rainfall less than 85% of normal. This, however, only confuses the issue, as it is clear that the occurrence of this level of rainfall over say, a year, is much more unusual and liable to result in a water shortage than over a shorter period of one month.

More recently, Tabony (1977a) suggested four simple indices of drought for use with rainfall and evaporation data. A simple measurement of "meteorological drought" is given by the fractional deviation of rainfall from the average, and as a refinement the use of rainfall minus potential evaporation, instead of just rainfall, is suggested. Tabony's index of "hydrological drought" is given by the value relating to the hydrologically effective rainfall, ie. the water surplus after evaporation has taken place and any soil moisture deficit has been removed. The fourth measure, that pertaining to "grassland drought" corresponds to the value obtained from the potential evaporation minus the actual evaporation effective for growth.



These four measures do not involve a set of standard time periods, and Tabony includes in his calculations the analysis of periods of various durations ranging from 30 days to 3 years. This feature allows for a more flexible measurement of drought over different time scales, and as Tabony illustrates, allows valid comparison between four different types of drought over any chosen duration, for one given location.

The only limitation of this technique, which also refers to the foregoing examples, is that it is of limited use for comparing droughts in different places. This is because the "abnormality" is measured in terms of its deviation relative to a specific normal value, and not on a "probability of occurrence" basis. In addition, such deviations are generally measured in relation to the mean of a distribution, which itself, in a skew distribution, may not represent a "normal" value.

#### C) Probabilites of deviations from normal

Although Yevjevich classifies this feature of a drought separately, it can reasonably be included as a measure "severity". Gibbs and Maher (1967) pioneered this approach, using data on rainfall, which they considered to be the most useful index of water supply. Their technique involves the division of cumulative frequency distributions of rainfall (annual and monthly) into 10 equally probable parts or "deciles". The first decile is the amount of rainfall which is not exceeded by the lowest

10% of the distribution, the second decile is the amount not exceeded by 20% of the distribution, and so on. The fifth decile corresponds to the median. "Decile ranges" are the ranges of rainfall values between deciles.

Use of this system to evaluate rainfall abnormalities by "decile ranges" produces a relative measure of deficiency or surplus, which is directly related to the "normal" or median conditions. This type of measurement is perhaps more useful than those discussed previously, in that rainfall distributions tend to be skew, and consequently abnormalities can be more meaningfully expressed in terms of a cumulative probability, rather than percentage deviations from average. In addition, this method allows better spatial comparisons of rainfall deficiency to be made. Indeed, Gibbs (1975) produced a series of maps of Australia depicting the nationwide distribution of decile range values for specific drought events.

#### D) Empirical indices

It is probably true to say that most measurements of drought developed to date are empirical in nature. The World Meteorological Organisation (1975a) give a comprehensive list, ranging from the relatively simple "precipitation factor" of Lang (1915), which is derived by dividing precipitation (mm) by temperature ( $^{\circ}\text{C}$ ), to much more complex ones. For example, Foley (1957) developed an "index of severity", obtained by dividing values of residual mass curves of rainfall by average annual rainfall.

Such dimensionless indices are very limited in their application if drought is to be regarded as a supply and demand phenomenon, because these two constituent parts cannot be measured in units which allow comparison. Subrahmanyam (1967), in stressing the need for such indices to have meaningful dimensions, recommended a water-balance approach, in which precipitation, potential evaporation and soil effects are combined.

Consequently, this particular approach, along with the preceding methods in parts (B) and (C) above, is employed to quantify the climatic abnormalities and the natural "supply" part of the drought examined in this thesis. Further consideration as to the applicability of these techniques in analysing the complete phenomenon of drought is given in Section 4.1.

### 2.3 THE HYDROMETEOROLOGICAL EVENTS OF 1971-76

The following pages concerning precipitation, evaporation and water balance analyse the characteristics of those climatic variables which are relevant to the 1971-76 period in Scotland. This is done bearing in mind the points raised in the foregoing discussion.

The extreme severity of all the above aspects of drought in one locality, ie. Edinburgh and East Lothian, in the early 1970's, has already been indicated in the Introduction, from the work of Thom and Ledger (1976) and

Ledger and Thom (1977). Now, the areal extent and severity of the hydrometeorological events of the 1970's will be considered for the whole of mainland Scotland, in order to form a national assessment of the drought. To assist with the identification of specific regions and locations referred to in the text, a map depicting administrative areas in Scotland is provided in Appendix 1.

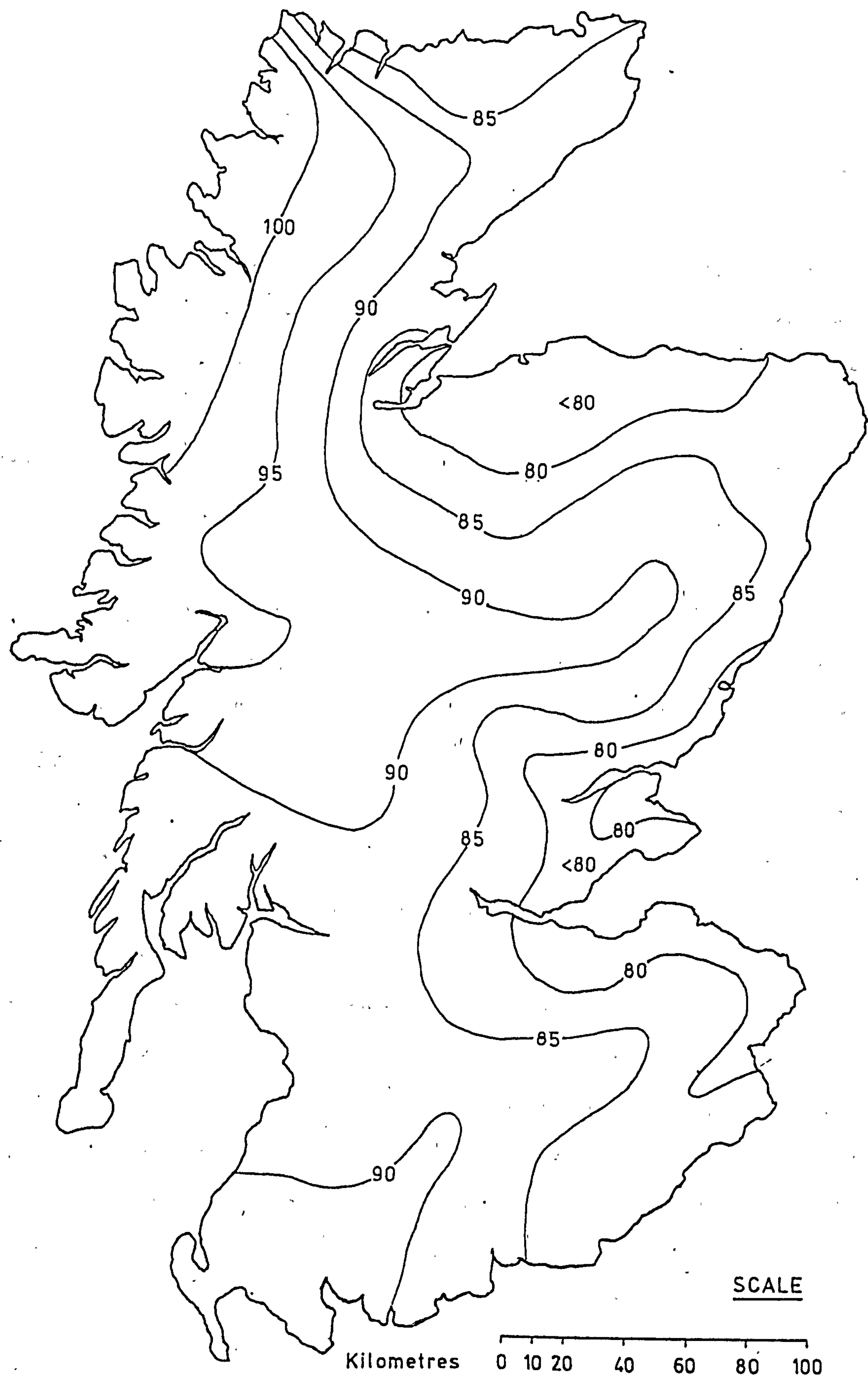
### 2.3.1 Precipitation

The Meteorological Office collects, collates and makes available data from all officially recognised rainfall stations in Scotland. It also produces isohyet maps of monthly and annual precipitation totals, expressed as a percentage of the 1941-70 average values. This thirty-year period is the current Meteorological Office standard meteorological period. Use of both the above types of information has been made in this study.

Annual rainfall totals for one hundred geographically dispersed stations have been used to construct the map shown in Fig. 2.1. This depicts isohyets representing the percentage of the 1941-70 average precipitation which fell during the six-year period, 1971-76. The areas experiencing the largest percentage reductions from average rainfall are clearly identified. For example, almost all of Banff, Moray and Nairn in the north-east; the the easternmost part of Tayside; most of Fife; and the



FIGURE 2.1 : The Percentage of Average (1941-70)  
Precipitation for the 6 - Year Period  
1971-76 in Scotland. (based on 100 stations)

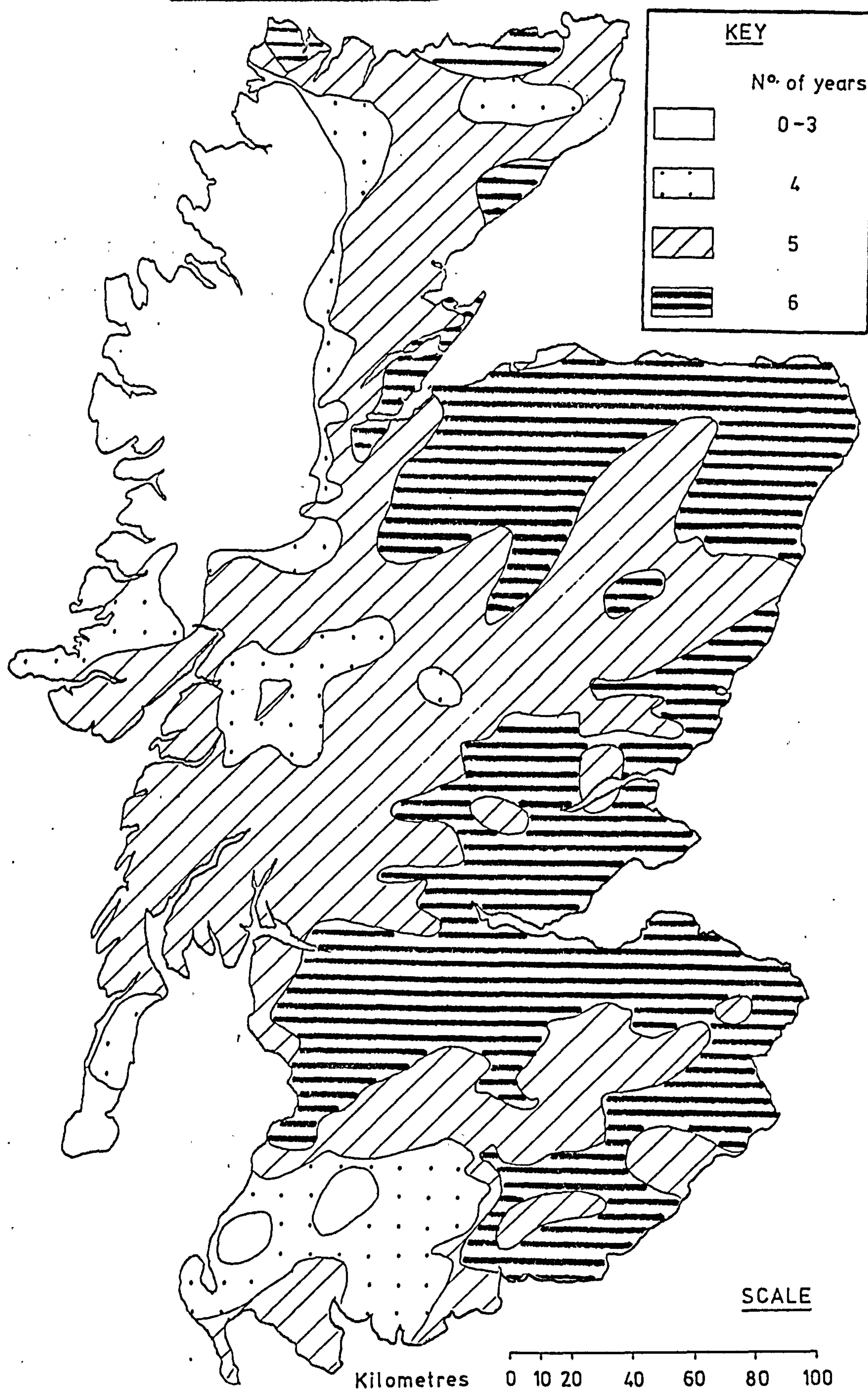


Lothians and Berwickshire in the south-east, received less than 80% of average for the six-year spell. The lowest percentage recorded was 77%, and this occurred in at least one location in all the areas specified above.

A notable feature of the isohyet pattern on Fig. 2.1 is that the 80, 85, and to a lesser extent, the 90% lines follow paths corresponding to the outline of the east coast, but transposed several kilometres inland. This reflects the fact that the principal cause of low precipitation was the occurrence of "blocking" high pressure systems over the North Sea. One of their effects is to reduce the frequency of the passage of the rain-bearing depressions over the eastern parts of Scotland, as noted by Brooks and Glasspoole (1928). Blocking anticyclones were unusually common in the early and mid 1970's (Dickson et al, 1975 and Perry, 1976) and thus can be identified as a major cause of the low precipitation experienced during this spell.

Of more importance than the total precipitation over the designated six-year period is its temporal distribution. Some insight is provided by Fig. 2.2, which has been derived from Meteorological Office annual isohyet maps, and illustrates the number of years in which precipitation was less than average during the 1971-76 period. The area which is identified as receiving less than average rainfall for all six years, closely corresponds to the isohyet pattern depicting the areas experiencing less than 85% of average rainfall over the six-year spell in Fig. 2.1. This would tend to indicate that the rainfall deficiency,

**FIGURE 2.2 : The number of Years With Less Than the 1941-70 Average Annual Precipitation Over the 1971-76 Period in Scotland.**





in terms of its relation to average, was spread over the entire six-year period for a large part of the country. In fact, three-quarters of the land area of mainland Scotland experienced at least five calendar years of less than average precipitation during the 1971-76 period.

Although the entire six-year period is shown to be one of reduced precipitation over much of Scotland, the driest part is clearly the first half. Fig. 2.3, based on the same stations as Fig. 2.1, reveals that precipitation totals over the three year period 1971-73 are typically a further 5 to 10 percent below 1941-70 averages than the 1971-76 totals. It can be seen that very nearly the entire eastern half of Scotland received less than 80% of average rainfall over the 1971-73 spell.

#### 2.3.1.1 Annual Pattern of Precipitation

Justification for the chosen study period (1971-76) can be had from consideration of annual precipitation totals for the years 1970-77 in Fig. 2.4. 1971 can be easily identified as the first year of a series experiencing less than average rainfall over most of Scotland. However, in the Lothian, Borders and Dumfries and Galloway regions in the south, it could be argued that 1970, or in some cases, 1969, saw the onset of the period of low rainfall. In these areas, annual precipitation was less than average for at least one of these two years. Despite this, 1971 seems to be an appropriate starting point of rainfall deficiency from the national viewpoint.

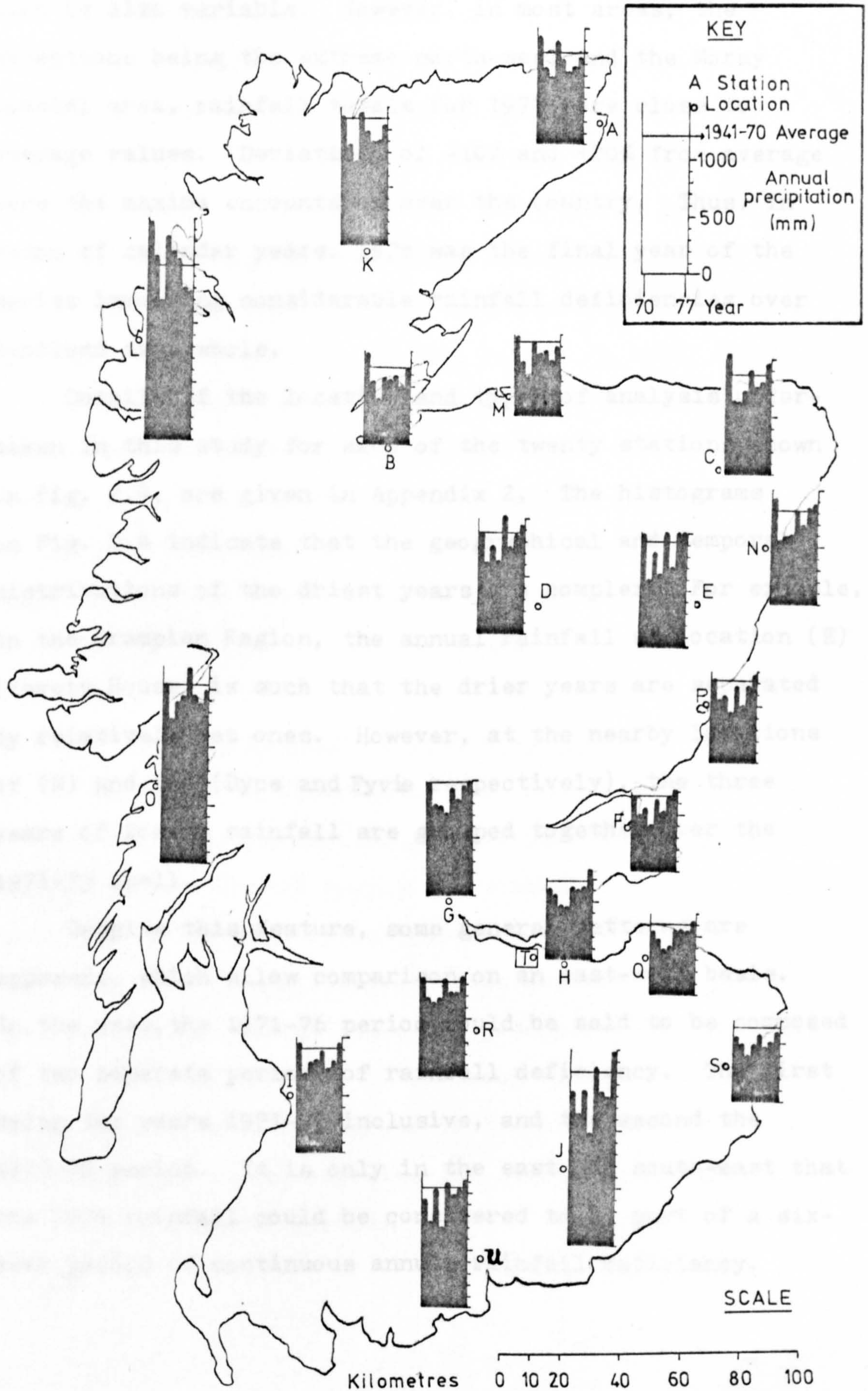


**FIGURE 2.3 : The Percentage of Average (1941-70)**  
**Precipitation for the 3-Year Period 1971-73**  
**in Scotland (based on 100 stations)**





**FIGURE 2.4 : Annual Precipitation for the Period 1970-77  
for 20 Representative Stations (listed in  
Appendix 2.1)**





The timing of the end of the period of low precipitation is also variable. However, in most areas, the exceptions being the extreme north-west and the Moray coastal area, rainfall totals for 1977 were close to average values. Deviations of -10% and +20% from average were the maxima encountered over the country. Thus, in terms of calendar years, 1976 was the final year of the series involving considerable rainfall deficiencies over Scotland as a whole.

Details of the location and types of analysis undertaken in this study for each of the twenty stations shown in Fig. 2.4, are given in Appendix 2. The histograms on Fig. 2.4 indicate that the geographical and temporal distributions of the driest years are complex. For example, in the Grampian Region, the annual rainfall at location (E) (Invery House) is such that the drier years are separated by relatively wet ones. However, at the nearby locations of (N) and (C) (Dyce and Fyvie respectively), the three years of lowest rainfall are grouped together over the 1971-73 spell.

Despite this feature, some general patterns are apparent, which allow comparison on an east-west basis. In the west, the 1971-76 period could be said to be composed of two separate periods of rainfall deficiency. The first being the years 1971-73 inclusive, and the second the 1975-76 period. It is only in the east and south-east that the 1974 rainfall could be considered to be part of a six-year period of continuous annual rainfall deficiency.

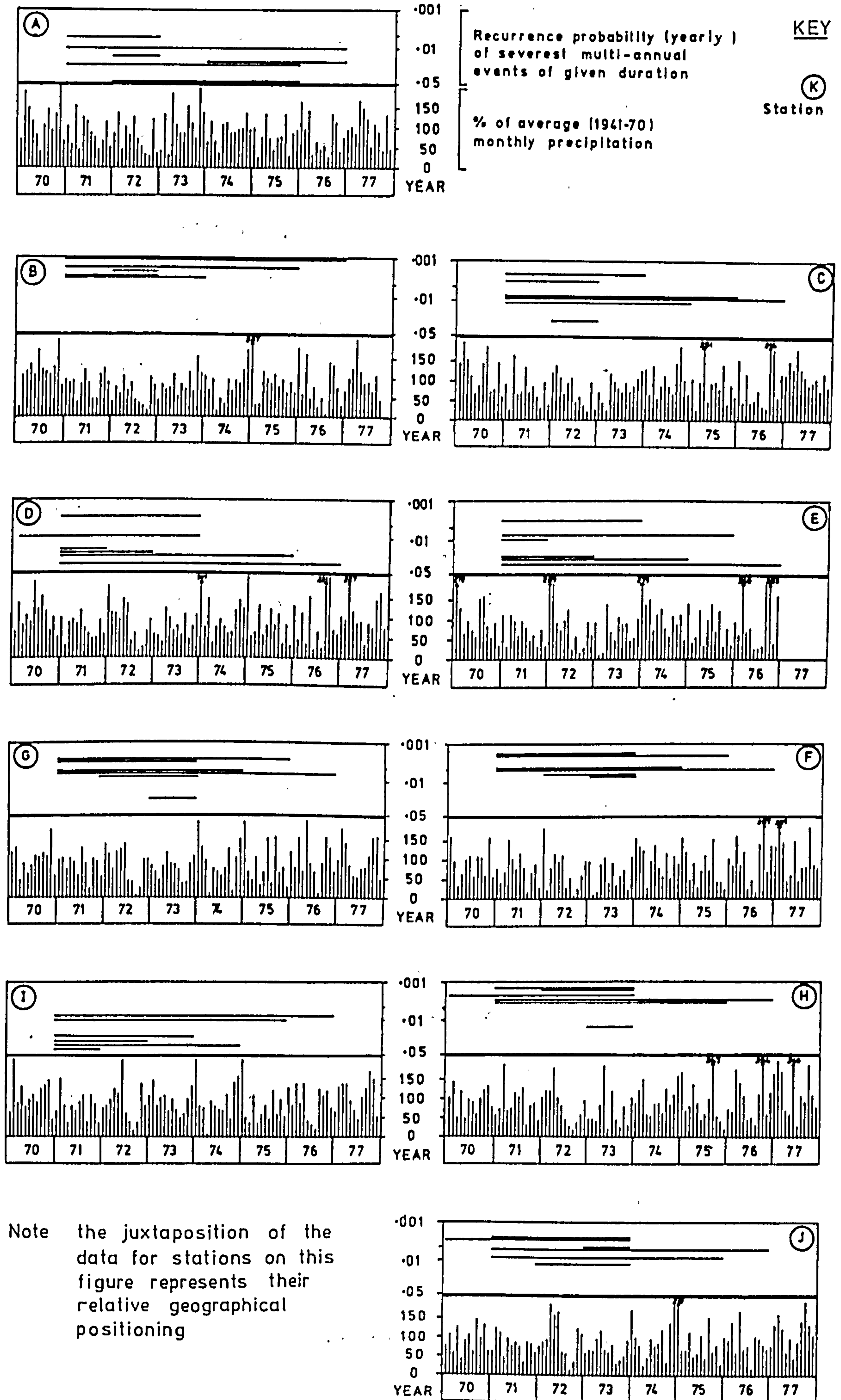
Another, but more obvious, feature of the annual rainfall distributions is that the 1971-73 spell was generally that of the lowest rainfall, although the pattern within this period varies considerably. For instance, there is considerable variation of the year of lowest rainfall. 1971 fits this description in southern parts of the Grampian Region and on the west coast. East Lothian and Berwickshire in the extreme south-east had their lowest annual rainfall totals in 1972, along with most northern parts, where the area around the Moray Firth received less than 60% of the annual average rainfall. Similar percentage values were experienced in 1973 in Fife, where, along with the eastern part of Tayside, West Lothian and parts of Dumfries and Galloway this was the driest of the six years.

#### 2.3.1.2 Monthly Pattern of Precipitation

The foregoing distributions of annual precipitation totals are somewhat limited for the purpose of identifying relevant low rainfall spells. A monthly time base allows much more meaningful investigation as to the seasonal nature of the rainfall deficiencies experienced. On Fig. 2.5, the percent of average (1941-70) precipitation for each month in the period 1970-77 is shown for 10 locations. These can be taken as representative of regions already identified as those receiving the lowest rainfalls relative to average over the period.



**FIGURE 2.5 : The Percentage of Average (1941-70) Monthly Precipitation and Recurrence Probabilities of THE Severest Multi-Annual Events for the 1971-76 Period for 10 Stations (located on Fig.2.4)**



From the diagrams for the selected stations, the general nationwide pattern of events can be summarised as follows.

In the far north, as represented by location (A) ie. Wick, 3 separate periods of markedly low rainfall can be identified. The first and longest lasts from mid-1971 to spring 1973, and the others occur over the whole of 1975, and during spring and summer 1976.

Moving south, the pattern at Inverness (B) is very similar, with the exception that the 1975 event is not really apparent. Towards the east (eg. Fyvie (C) ) the first dry period begins relatively early, at the onset of 1971 and continues until April 1973. The second, initiating in mid-1975, lasts until September 1976.

Further south, though still in the Grampian Region, the same pattern is displayed at Braemar (D) and Invery House (E). However, the major difference is that the first dry period, although continuing to the end of 1973, is punctuated by relatively high rainfall at the beginning of 1972.

In the Central Lowlands, the main dry spell begins in mid-1971 in Fife (Leuchars, location (F) ), and in mid-1972 further inland (Bridge of Allan (G) ). This spell is similarly extended until the end of 1974 at Leuchars, whilst it ends one year earlier at Bridge of Allan. In both locations, the dry spells of late 1975 and summer 1976 are separated by several months of greater than average rainfall.

Moving progressively southward, the pattern of events at Blackford Hill (H) in the Lothian Region, and at

Eskdalemuir (J) in the Borders, is very similar to that described for Bridge of Allan above.

In the south-west, however, as illustrated by data for Prestwick (I) the dry periods are short and interrupted by relatively wet spells, typically in the winter months. For example, the longest run of months with less than average rainfall lasted for 5 months in mid-1971 at Prestwick, compared with a series of 11 months over 1972/73 at Blackford Hill in the east.

In summary, regarding the seasonal nature of low rainfall events, the following points are worth noting.

(i) The major low rainfall period included in the years 1971-73 began earlier and ended earlier, typically in spring 1973, in the Highland region and the northern part of the Grampian region. Further south, this dry period tended to terminate at the end of a year, be it 1972, 73 or even 74, the more eastern locations having the longer durations.

(ii) The dry spells of summer 1974, autumn and winter 1975 and summer 1976 were generally isolated events, there being intervening wet periods. Only in the Grampian and Highland regions could the rainfall deficiencies of 1975 and 76 be considered as one continuous event.

#### 2.3.1.3 Recurrence Probabilities of Precipitation Events

The foregoing assessment of percentage deviations from average precipitation values omits one important

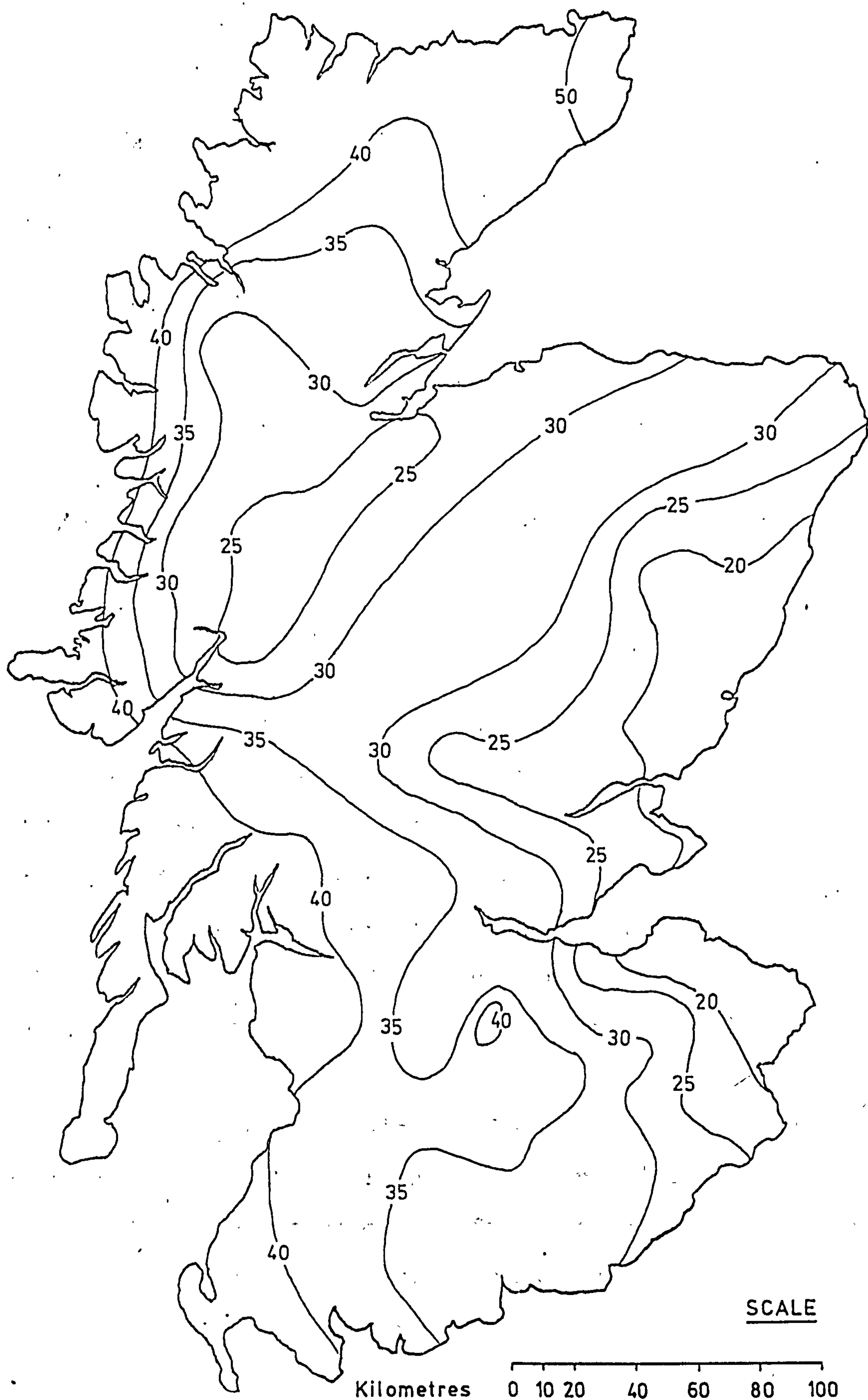
factor, ie. the inherent degree of variation in rainfall over different parts of the country. Fig. 2.6, provided by the Meteorological Office, which represents the areal distribution of return periods (in years) for the incidence of 75% of average annual rainfall, can be taken as an example. There is a general pattern of increased likelihood of low precipitation, in terms of percentage deviation from average, from west to east. This holds true for the southern half of the country, but in the north, the area of most variable rainfall is centred around Inverness and Lochaber. It would be interesting to take account of this inherent regional variation, by considering the recurrence probabilities of the low rainfall events of the 1970's, to discover whether the earlier pattern of severity is still apparent.

The derivation of return periods or recurrence probabilities of rainfall events has to meet several requirements to be of acceptable reliability. Firstly, a long period of record is required, and secondly the variation within the chosen data series must be representative of the "normal" or expected distribution of all degrees of variation.

Tabony (1977b) describes a technique for calculating the return periods of deviations of rainfall from 1941-70 average values, on a monthly basis. In his methodology, a distribution of the monthly rainfall series over the period 1911-70 is evaluated by a coefficient of variation and a coefficient of skewness. Consequently, a log-normal



**FIGURE 2.6 : The Return Period (in Years) of the Occurrence of 75% of Average (1941-70) Annual Precipitation**  
**Source : Meteorological Office**



frequency distribution can be fitted, and then used to estimate the probabilities of recurrence of given variations in rainfall, over periods of any number of months.

This method is, in essence, that used by the Meteorological Office (1979), for estimating rainfall return periods, on both point and areal bases, and the probabilities in Fig. 2.5 are derived from Meteorological Office tables. However, the possible shortcomings of this technique have to be considered prior to any analysis of the obtained values. Firstly, the 60-year period from 1911 to 1970 is rather short, there being several records available over longer durations in Scotland. There is also reason for doubting its representativeness of the "normal" degree of climatic variation. For instance, this period is centred around the relatively mild and wet spell of approximately 1920-1950 (Lamb 1966). An indication of the possible bias involved can be gauged from data presented later in Section 2.6. As an example, if the period used had been displaced just ten years to say, 1921-80, the inclusion of the unusually dry periods in the early and middle 1970's would in all probability greatly decrease the calculated return periods of low rainfall events.

Lastly, the Meteorological Office calculations assume that each month of the year has a similar frequency distribution of variation of rainfall totals. Whereas this may be true in some instances, as shown by Tabony, it

cannot be guaranteed for all locations. Thus, the probabilities on Fig. 2.5 are restricted to calendar periods of 1 to 6 years to avoid errors caused by the above assumption.

Return periods listed in Meteorological Office tables extend to 1,000 years, which is a rather over-optimistic figure to be based on a 60-year record. For certain locations, notably in Moray and Nairn in the north-east, and in Fife, East Lothian and Berwickshire in the south-east, some multi-annual rainfall events of the 1971-76 period were found to correspond to return periods greater than 1,000 years. In such cases it was decided not to display the information on Fig. 2.5. For the 10 locations represented, only tentative analysis of the various annual recurrence probabilities ranging from 0.05 to 0.001 (ie. return periods of 20 to 1,000 years) is justified, for the reasons given above.

Even if absolute values cannot be used, it should nevertheless be possible to make relative comparisons on the following basis;

- (i) the order of probabilities associated with events of different durations for one location; and
- (ii) the order of probabilities for a given duration for different locations.

In the case of (i) above, intra-station comparison *indicates* ~~events~~ that the 3-year rainfall event was the most abnormal one in the country. The 1971-73 event has the lowest recurrence probability at 6 locations (Fyvie (C),

Braemar (D), Invery (E), Leuchars (F), Blackford Hill (H) and Eskdalemuir (J) ), and the second lowest at Bridge of Allan (G). At Inverness (B) and Prestwick (I), the 6-year event was the most unusual, whilst it was the 2-year rainfall at Wick (A). Of events over all six durations, the 1-year rainfalls are generally those of the least abnormal nature.

Consideration of (ii) above is limited by the fact that some stations are omitted from the analysis represented in Fig. 2.5. However, it is possible to make the following generalisations regarding the least and worst affected areas. Taking the former first, the highest probabilities of recurrence (~~in years~~<sup>ly</sup> ~~x~~<sup>1</sup>) are those relating to; 3 to 6-year events at Wick; 1 to 5-year events at Prestwick; and 5 and 6-year events at Braemar.

Conversely, the lowest recurrence probabilities can be associated with rainfall over the following areas and durations;

a) the area around the Moray Firth, including Moray and Nairn, over 1, 2, 4, 5 and 6-year periods;

b) the area surrounding the Firth of Forth ie. Fife, the Lothians and Berwickshire, over 2, 3, and 4-year periods.

### 2.3.2 Potential Evaporation

Although water shortage in drought is usually associated mainly with rainfall deficiency (particulary in a climate such as Scotland's), the other climatic



influence of evaporation must also be considered.

The major problem in dealing with this variable is the lack of data which is apparent in both spatial and temporal terms. For instance, the Meteorological Office (1979) consider measurements at only five sites on the Scottish mainland to be sufficiently accurate for the purposes of scientific analysis. In fact, these are the only locations for which the full formula of Penman (1948) is used to calculate potential evaporation ( $E_p$ ). The records for the five stations go back just over twenty years.

#### 2.3.2.1 Annual Pattern of $E_p$ .

The percentages of average annual potential evaporation (based on the Meteorological Office's adopted standard period of 1956-75) for the five stations are shown in Table 2.1 for the years of interest. The precise location of each is shown in Fig. 2.7.

Over the five locations, the total  $E_p$  for the 1971-76 period is between 4 and 12% above average. However, the major contributions to these increases were made during the latter three years. This distinction is less apparent for the two most northerly locations, Kinloss and Dyce, but at Prestwick in the south-west, where the least overall increase was experienced, all the years 1971 to 73 inclusive had below average  $E_p$  values. The three easternmost stations experienced their highest-ever

annual Ep values during the latter three years of the 1971-76 period; Turnhouse in 1974, Dyce in 1975 and Leuchars in 1976.

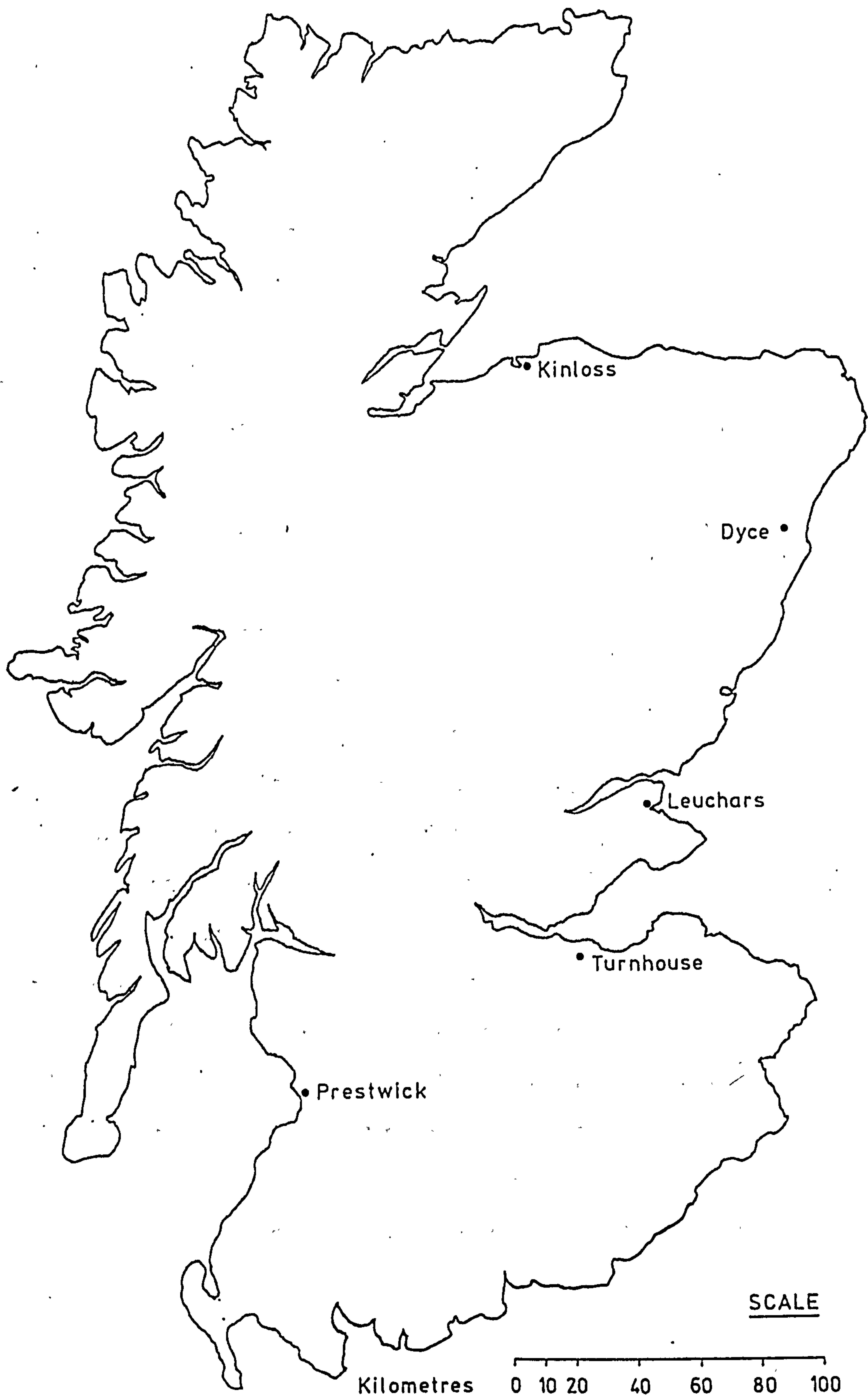
TABLE 2.1 Percentage of Average Annual Ep During the 1971-76 Period for Five Stations.

Station	% of average Ep for year						6-year (1971-76) % of average
	'71	'72	'73	'74	'75	'76	
Kinloss	107.9	103.9	102.1	106.9	101.1	107.7	104.9
Dyce	112.3	104.8	108.6	112.0	116.6	113.6	111.3
Leuchars	100.0	99.4	104.8	110.0	112.2	113.9	106.7
Turnhouse	100.9	101.3	101.8	115.7	114.6	111.9	107.7
Prestwick	97.3	95.6	95.7	112.5	111.1	113.4	104.3

#### 2.3.2.2 Monthly Pattern of Ep

The possible methods of analysis of monthly Ep values have to be considered carefully because of its distinctive seasonal variation (shown for each station in Figs. 2.8.1 to 2.8.5). If, for example, percentage deviations from the mean are calculated, because monthly mean values vary

**FIGURE 2.7 : The Location of Potential Evaporation  
Stations Referred to in this Thesis**



over the year by a factor of at least 10, then a given percentage deviation in summer will be about 10 times the same relative deviation in winter. Such treatment of data could therefore result in a misrepresentation of actual events. Consequently, it is more constructive to measure absolute deviations from average values, in terms of mm. This is because the range of such deviations for all seasons is of a similar order; all differences between maximum deviations in different months being of a factor less than 2 for each location. A monthly series of absolute deviations from average values is shown for each location in Figs. 2.8.1 to 2.8.5.

An alternative monthly analysis based on recurrence probabilities is presented on the same figure. Of course, a probability assessment of the monthly Ep data will be somewhat limited in usefulness and scope by the short period of record available. In respect of this consideration, only a rudimentary percentile analysis has been carried out. Simple ranking of the 12 monthly sets of 20 annual periods allows the two highest Ep values to be included in the first decile, the next two highest in the second decile and so on, for each month of the year. Those months in the first and second deciles of their distributions are indicated in Figs. 2.8.1 to 2.8.5.

Use of the two above types of analysis can be made to identify the pattern of unusual Ep values on a monthly time base, and the most notable events are now given further



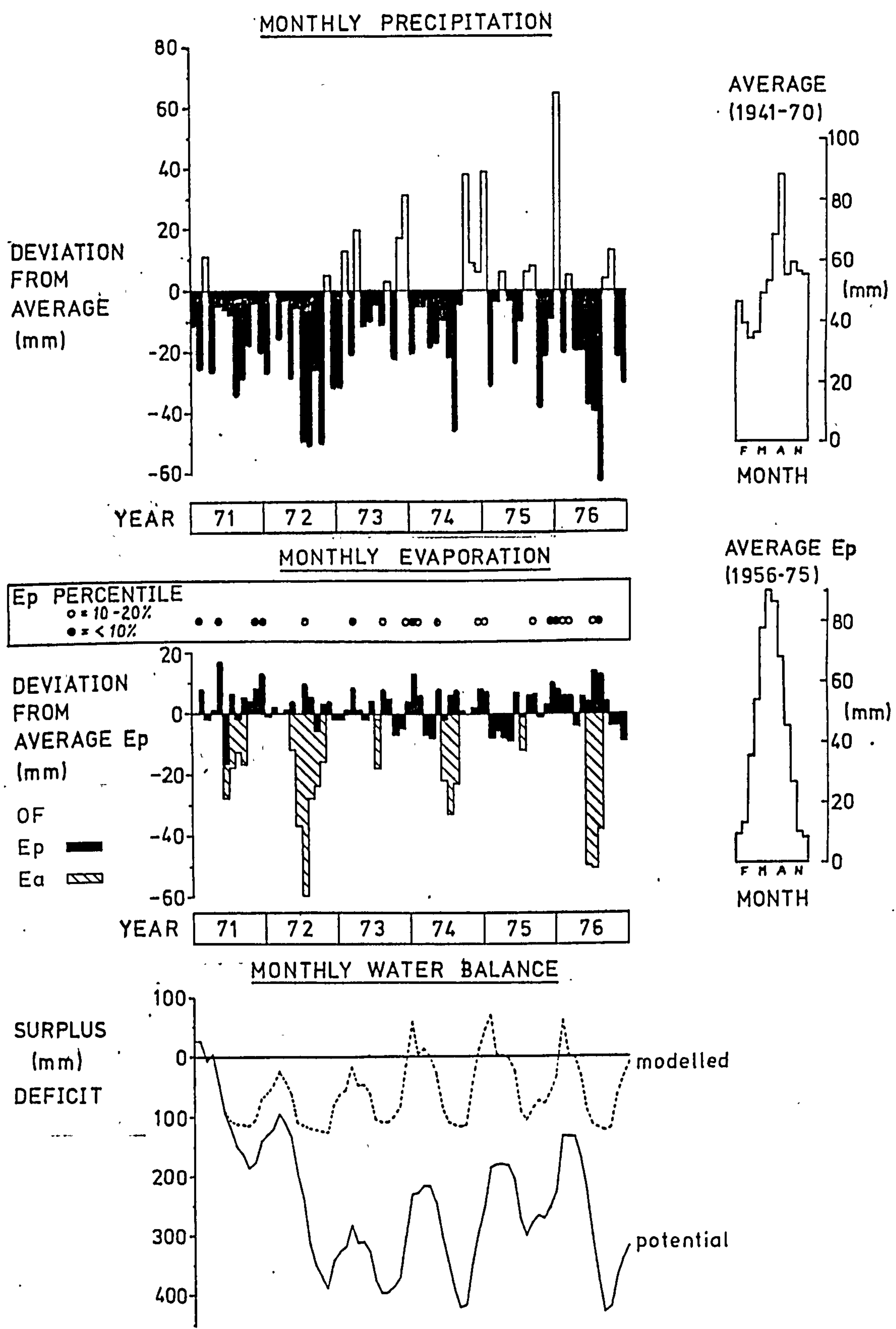
consideration. During the first three years of the 1971-76 period, the only sustained spell of abnormally high monthly Ep values occurred throughout 1971 in the 2 northernmost locations, Dyce and Kinloss. The increased potential evaporation values throughout the year 1974 are apparent at all 5 stations, and for Dyce and Leuchars on the east coast, this pattern is sustained right through 1975 to September 1976. In two of the other locations, ie. Prestwick and Turnhouse, only the middle months of 1975 involve notably high Ep values. The subsequent high Ep values of 1976 are confined to the summer months at these two places. At Kinloss, however, a relatively uninterrupted spell of high monthly potential evaporation was recorded from Autumn 1975 to September 1976.

### 2.3.3 Water Balance

An assessment of "water-balance" allows the effects of the two previously discussed influences (precipitation and potential evaporation), and also that of soil effects (Subrahmanyam 1967), on water availability to be compared and combined.

Figs. 2.8.1 to 2.8.5 allow such a comparison to be made for the five locations on Fig. 2.7, between absolute monthly deviations in rainfall, and Ep. Visual inspection of the histograms reveals that no consistent patterns are apparent as regards a relation between monthly rainfall deficiencies and above average Ep values. However, the

FIGURE 2.8.1 : Monthly Deviations of Precipitation and Ep From Average, and Potential and Modelled Water Balances, for the 1971-76 Period at Kinloss



**FIGURE 2.8.2 : Monthly Deviations of Precipitation and  
Ep From Average, and Potential and Modelled  
Water Balances, for the 1971-76 Period  
at Dyce**

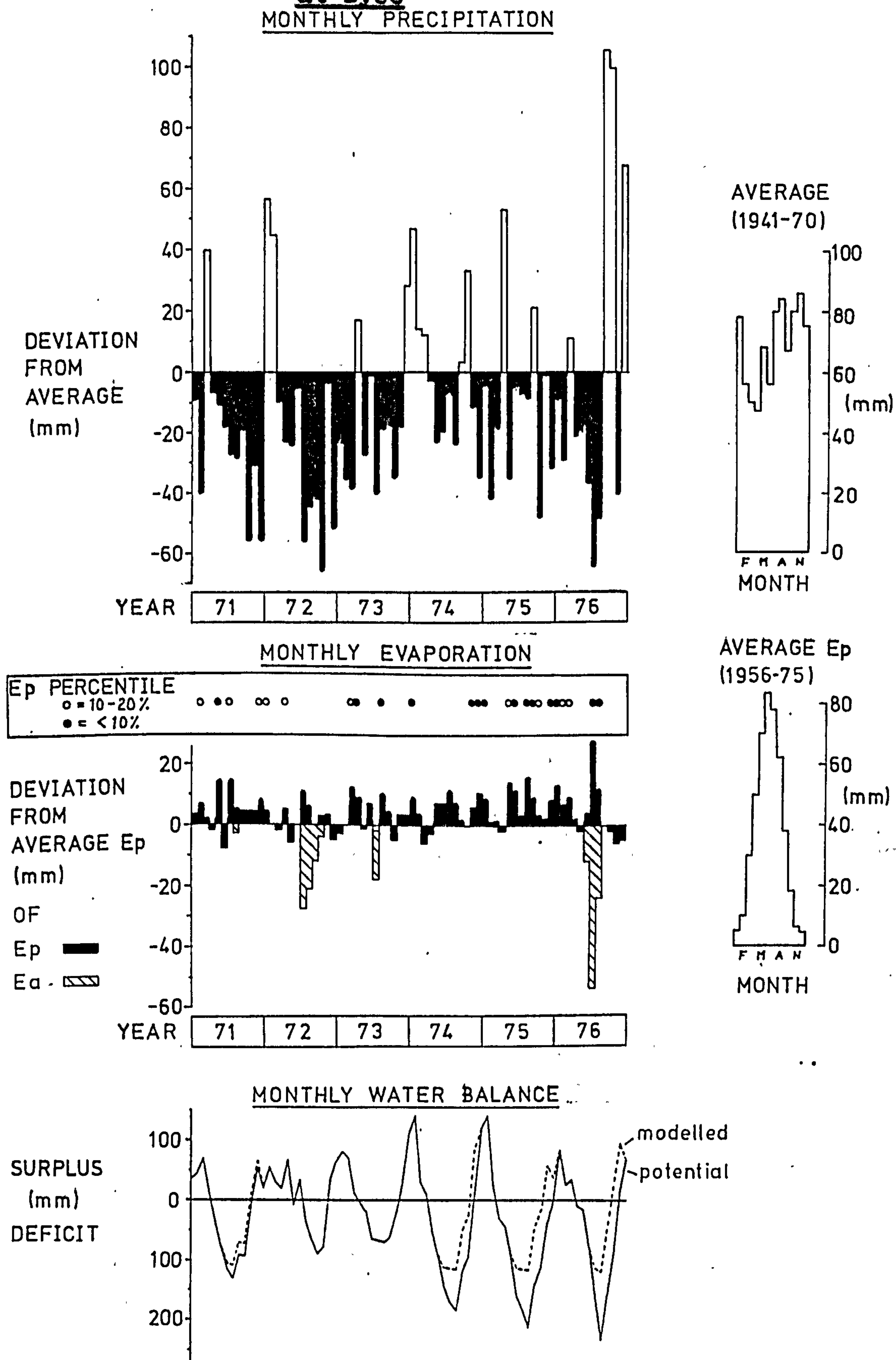


FIGURE 2.8.3 : Monthly Deviations of Precipitation and Ep From Average, and Potential and Modelled Water Balances, for the 1971-76 Period at Leuchars

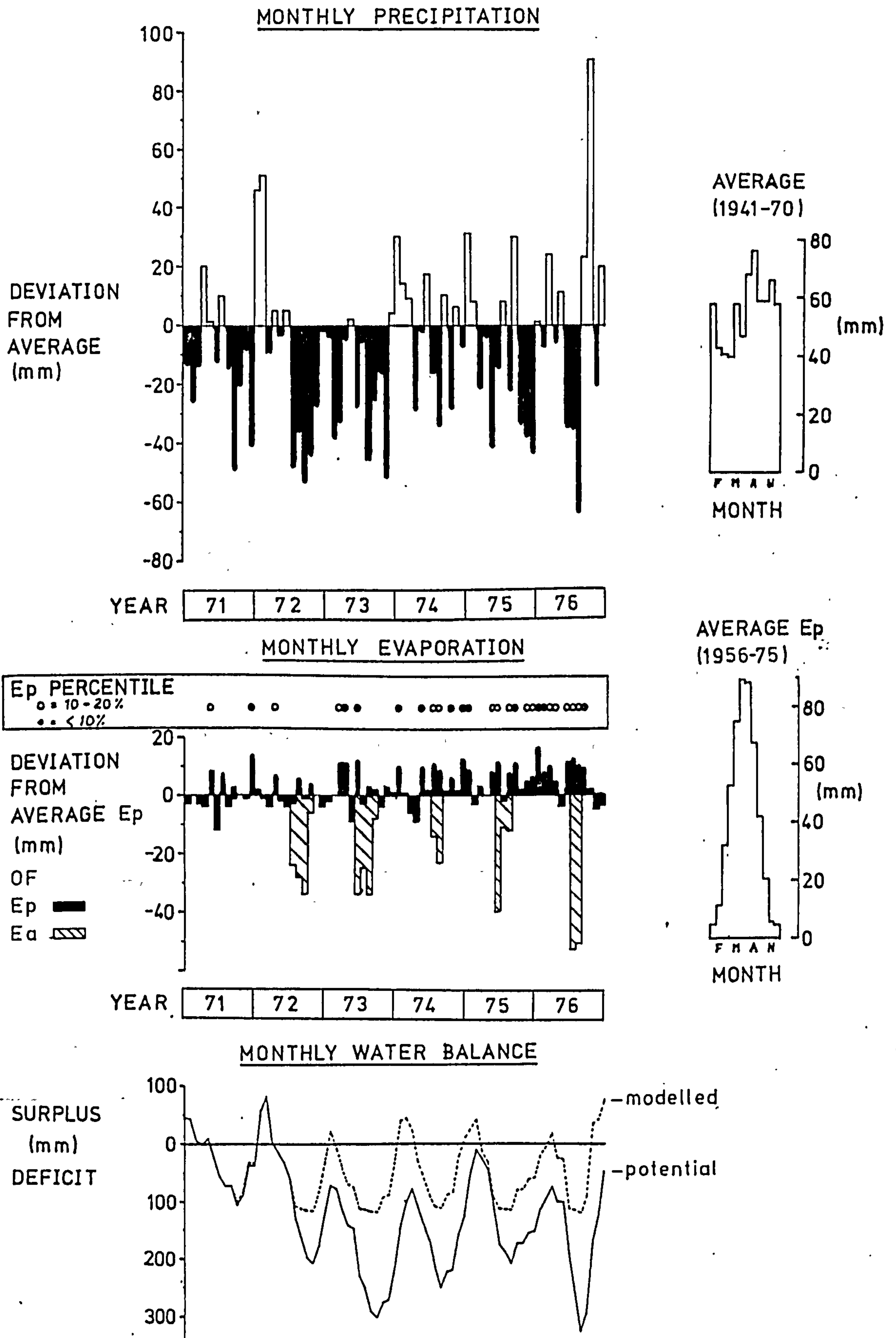
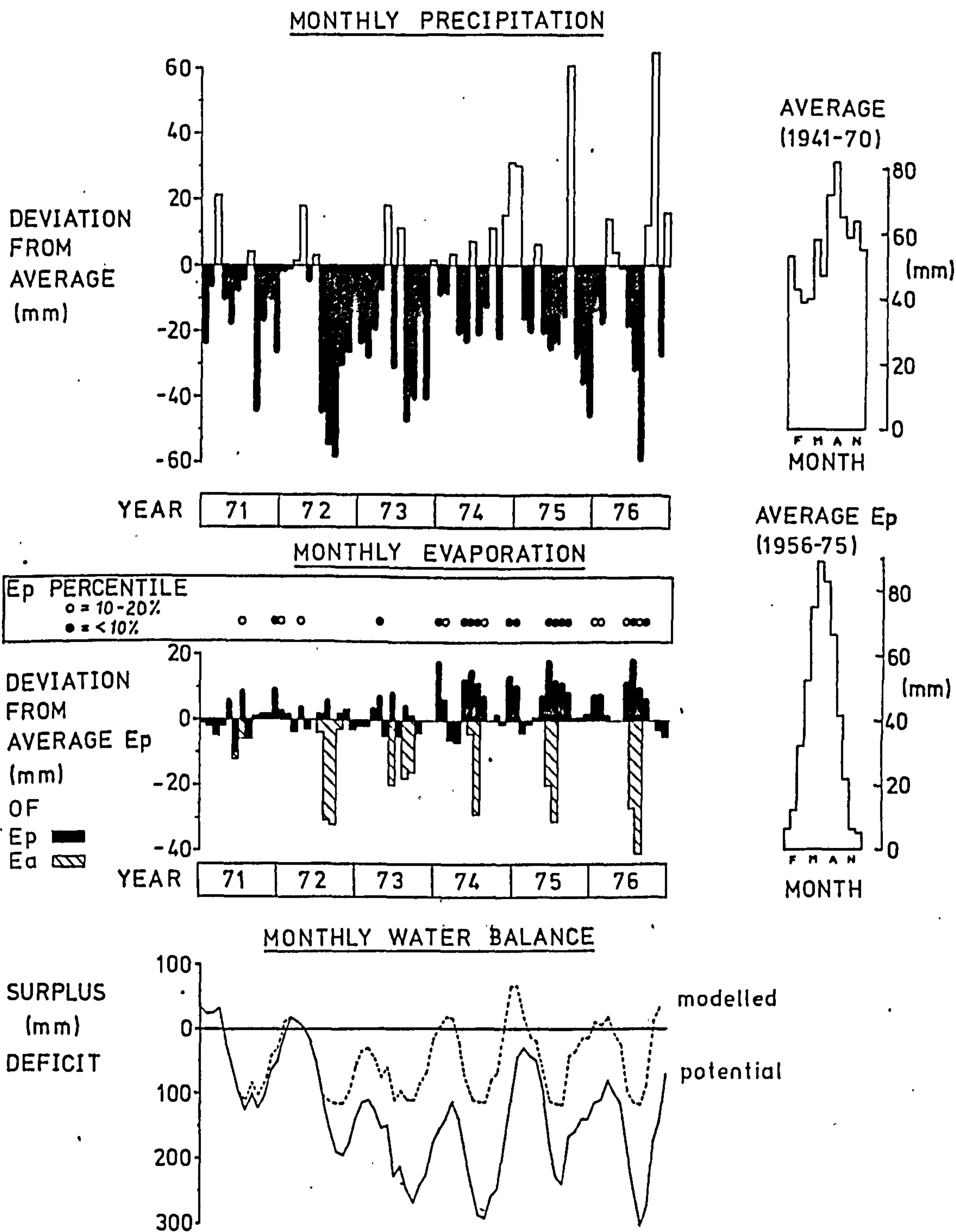
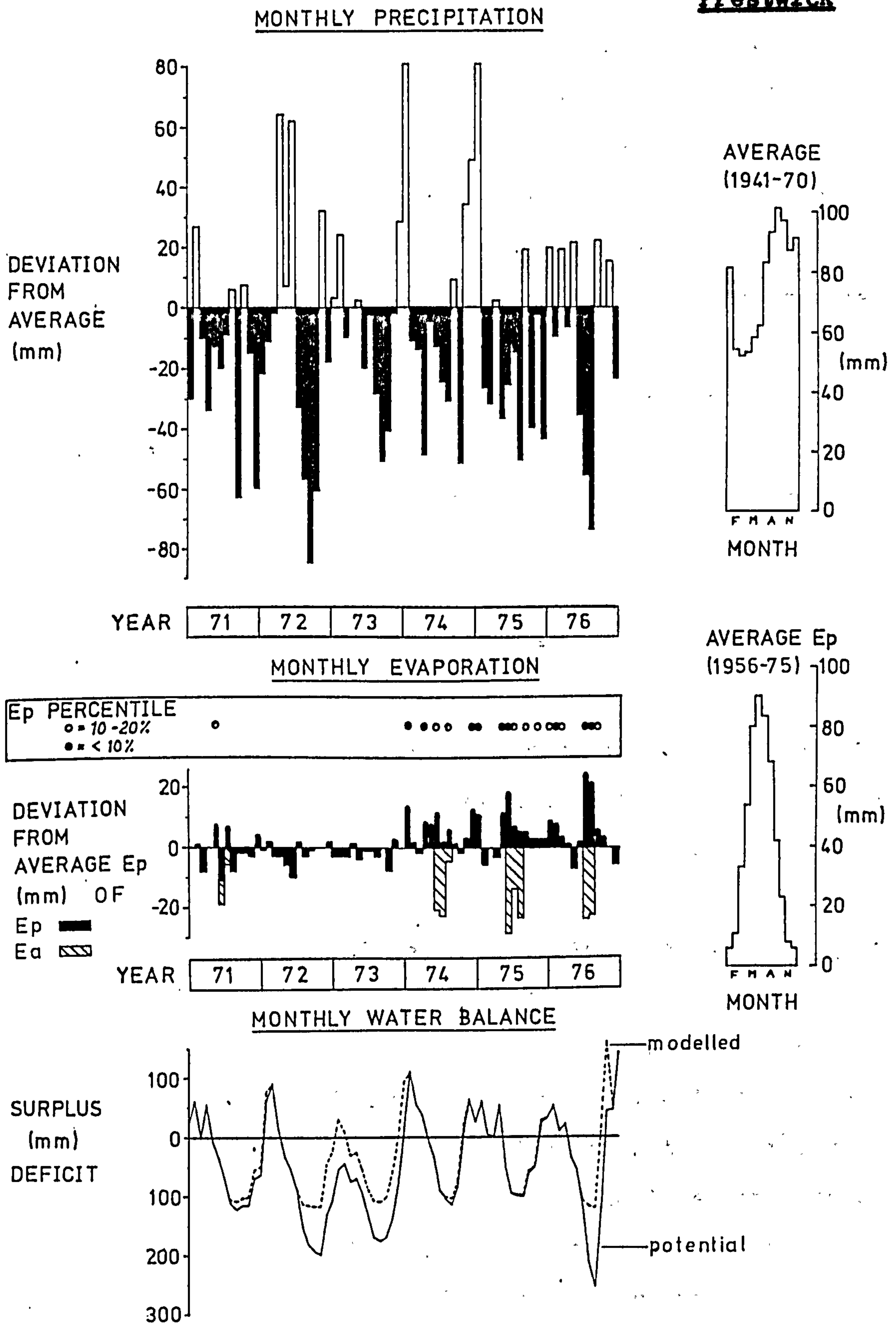




FIGURE 2.8.4 : Monthly Deviations of Precipitation and Ep  
From Average, and Potential and Modelled  
Water Balances, for the 1971-76 Period  
at Turnhouse



**FIGURE 2.8.5 : Monthly Deviations of Precipitation and Ep From Average, and Potential and Modelled Water Balances, for the 1971-76 Period at Prestwick**



same two distinctive parts of the entire six-year period from 1971 to 76 are once again apparent. Apart perhaps from the events of 1971 in the north-east, the incidence of less than average rainfall over the 1971-73 period cannot be consistently associated with either markedly high or low  $E_p$  values. Contrastingly, the latter half of the drought period, ie. the years 1974, 75 and especially 1976, display a pronounced association between months of low rainfall and those of relatively high potential evaporation.

Thus, it is apparent that whereas deviations from average  $E_p$  values may have played a rather insignificant part in the earlier drought years, they seem to have been a much more important feature of subsequent dry spells. Even so, typical maximum monthly increases in  $E_p$  over average values are, in absolute terms, only approximately one-third of monthly rainfall deficiencies for all 5 locations, as Figs. 2.8.1 to 2.8.5 illustrate.

#### 2.3.3.1 Comparison of Potential and Modelled Water Balances

Figs. 2.8.1 to 2.8.5 also include water balances based on the monthly values displayed above them. In all cases, consideration of the previous year's precipitation and potential evaporation justifies the starting point of zero deficit in 1970. The solid line represents the potential water balance, and the dotted path an alternative one based on a 75mm "root constant". The method used in its deviation is that of Penman (1949),

*iv*



whereby it is assumed that soil moisture is readily evaporated via vegetation up to a specified limit or "root constant", after which evaporation continues at a much reduced rate. Appendix 3 shows the relationship between potential maximum seasonal soil moisture deficit and that modelled for a root constant of 75mm.

This simple model is intended as a closer approximation to actual events, and can be regarded as such since it simulates the evapotranspirational behaviour of short-rooted vegetation, which probably covers the greatest proportion of land in most parts of the study area. Further, it allows an estimation of  $E_a$  (the resulting evaporation occurring with the root constant applied) to be taken into account. The hatched areas in Figs. 2.8.1 to 2.8.5 show the deviations in  $E_a$  from  $E_p$  due to this consideration.

At this point, the limitations of the above monthly treatment of rainfall and  $E_p$  data to derive water balances should be noted. Grindley (1967) indicated the possible errors that can occur when no account is taken of the distribution of these two climatic variables during each month, and particularly spring months, over which the rate of  $E_p$  tends to increase relatively quickly. Grindley quotes a somewhat extreme example involving a 33mm underestimate of a season's maximum soil moisture deficit. Such a level of discrepancy should be regarded as near the maximum possible, and it is likely that over a period of six years successive errors in monthly estimates of water



balance should cancel each other out to a large extent.

The graphs depicting the course of the potential water balance (Figs. 2.8.1 to 2.8.5) from 1971 to 76, for the most part, represent highly irregular conditions. For example, for the three locations nearest the east coast, ie. Turnhouse, Leuchars and Kinloss, the presence of a permanent soil moisture deficit and hence no water surplus, is indicated from 1972 (1971 in the case of Kinloss) to at least the end of 1976. The peak values of potential moisture deficit for the three sites are all over 300mm. Contrastingly, at Dyce, the longest spell of potential moisture deficit occurs during 1972-73, and lasts 20 months. In the west, at Prestwick, the water balance shows a seasonal water surplus over a period of at least 3 months in each year.

Consequently, in terms of durations of deficits, the application of the 75mm root constant model makes negligible differences at Prestwick and Dyce. In the former, the major differences in magnitude occur in the summers of high  $E_p$  and low rainfall from 1974-76. At Dyce, the longest period of difference is during the years 1972-73, and a deviation in soil moisture deficit between potential and modelled occurs in the summer of 1976. The actual monthly deviations of  $E_a$  from  $E_p$  resulting from the above comparisons are shown by the hatched areas in Figs. 2.8.1 to 2.8.5.

For the 3 sites experiencing the greatest potential moisture deficits, the inclusion of the modelled values

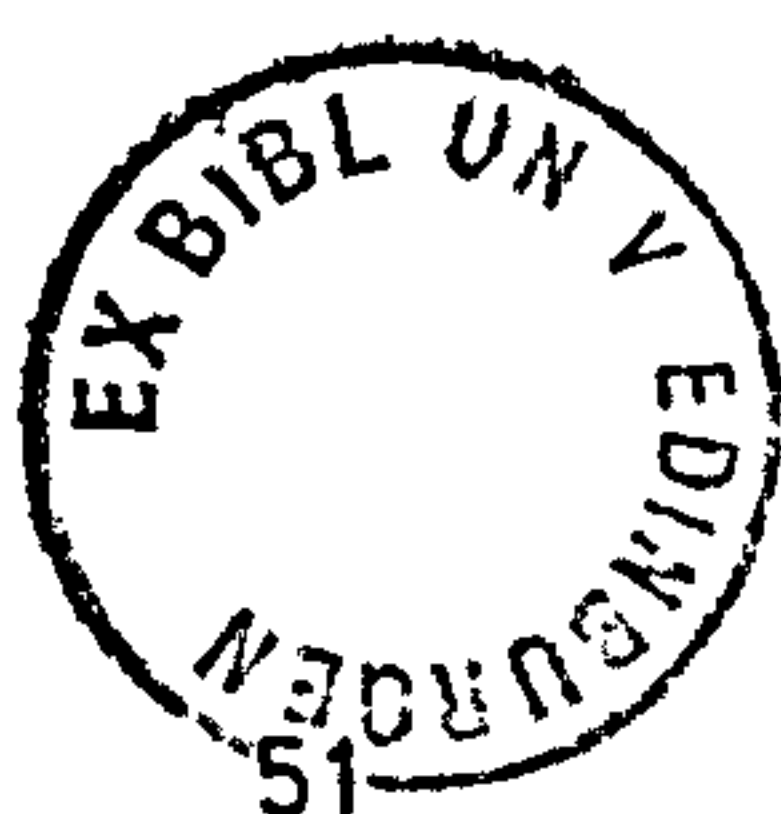
provides a pronounced contrast. For example, they produce a water surplus at Leuchars during each year of the period, and <sup>4</sup>one in 5, and 4 out of 6 years at Turnhouse and Kinloss respectively.

Thus, for these 3 stations, the 75mm root constant model suggests very large differences in  $E_p$  and  $E_a$  during summer months, as is shown in Figs. 2.8.1 to 2.8.5. In general, over the 1971-76, period such deviations are more frequent, more severe in terms of mm per month, and of longer duration than for Dyce and Prestwick.

Now, if it is assumed that as in the model, much of the potential evaporation would not take place in the actual circumstances, this has an important bearing. In the more eastern locations, the increased  $E_p$  values would probably be of little significance in affecting soil moisture, and consequently run-off levels. However, at the wetter sites further inland and to the west, the increased potential evaporations experienced could be expected to have a relatively greater influence on quantities of water available in the soil and in water-courses.

#### 2.3.4 Hydrometeorological Summary

In the light of the issues raised in the earlier parts of this section concerning definitions and measures of drought, it would appear that the hydrometeorological events in eastern Scotland during the 1971-76 period, at this stage, merit association with the term "drought" as





defined previously. The following aspects of the climate over these years are those of most significance to this thesis.

The three-year precipitation totals for the period 1971-73 were less than 80% of the 1941-70 average over the entire eastern half of Scotland. This figure is of particular relevance in that it has been widely used to assess the reliable yields of water supply reservoirs, after work by Binnie (1892) and Glasspoole (1924). Therefore, it could be expected that such reservoirs in eastern Scotland might have been unable to supply their official yields in the early 1970's.

In this same part of the country, particularly dry spells, of varying duration, tended to terminate towards the end of given years, notably 1972 and 1973. Since impounding reservoirs would be at their maximum depletion at this time of year, this fact would indicate the likelihood of further problems in the sphere of water supply provision.

The most notable low precipitation event, ie. that spanning the years 1971-73, would appear to be of a most unusual and extreme nature. Return periods of 200 to 1,000 years for locations in the eastern half of Scotland are indicated by Meteorological Office calculations.

Over this same three year period, recorded potential evaporation values did not differ markedly from average ones. Unusually high  $E_p$ 's were recorded in the years

1974-76, and were noticeably coincident with spells of low monthly precipitation. In this three-year period Ep values in eastern Scotland were typically 10 to 15% above average. Such percentage deviations, and particularly the corresponding absolute deviations from average values were much smaller than those concerning precipitation during the 1971-76 period.

The combination of the abnormally low monthly precipitation totals, and the high levels of potential evaporation has resulted in some unusual patterns of potential moisture deficit. Sites near the east coast of Scotland experienced continuous potential moisture deficits over the four-year spell from 1972 to 76, with seasonal peaks of over 300mm. Such occurrences are very rare in Scotland, as is indicated by Ledger and Thom's (1977) derivation of a two hundred year long record of potential moisture deficit for the Edinburgh area.

When actual water balances, simulated by the application of a 75mm "root constant" are considered, the geographical importance of the unusually high potential evaporation values experienced would appear to be limited. Only in the more western and generally wetter areas could the greater than average levels of Ep have had a marked effect, during a period of low rainfall, by further reducing water availability in the soil, and ultimately in the watercourses. As regards this latter matter however, it is most appropriate to examine the hydrological



nature of the 1971-76 period with direct reference to river flow data. Such an investigation now follows.

## 2.4 RUN-OFF DURING THE 1971-76 PERIOD

### 2.4.1 Availability and Suitability of Run-off Data

To assess the effect of the extreme hydrometeorological events of the 1971-76 period on water resources in Scotland, an analysis of run-off and river flows is required. The responsibility for monitoring and recording the discharge of rivers and streams in Scotland lies with seven River Purification Boards. The areas under each Board are shown in Appendix 1.

Since all of these bodies have been formed within the past thirty years, then river flow records tend to be of rather short durations. In 1978, only 24 records extending to more than twenty years were available for the whole of Scotland, and the majority of these were concentrated on the two major rivers developed for hydroelectric power generation, the R. Spey and R. Tay. The detailed distribution of the length of continuous records available up to 1978, shown in Fig. 2.9, reveals that generally the shorter durations are more common. An exception occurs in the 16 to 20 year duration class, which corresponds to a period of a high rate of installment of river gauging stations particularly in the Tweed, Forth and Clyde R.P.B. areas. During the relevant five-year period from 1959-63, a total of 41 new river gauging stations were commissioned in Scotland as a whole.

However, not all river flow records are suitable for this study, so several criteria were used to select suitable river gauging station records for analysis. All records under consideration were made subject to the following conditions.

(i) Accuracy of measurement

This was assessed on the advice from the relevant gauging authority. Those records considered to be unreliable, especially as regards low flows, were disregarded. Unfortunately, this condition resulted in the partial exclusion of the longest run-off record in the country, measured at Woodend on the R. Dee since 1930, much of which is considered to be unreliable at extreme low flows.

(ii) Extent of artificial influences on flow

Providing that the volumes of water associated with such influences were known over the period of record under concern, then flow records were considered acceptable. This requirement means that relatively long records on the R. Tay, dating from the 1950's could not be used because of the development of hydro-power schemes in the river's upper reaches during the latter part of this decade.

(iii) Catchment size

Since it is the intention to make comparisons of

run-off over different parts of the country, it is considered that some standardisation of catchment size is necessary. This safeguard should limit the inclusion of variables dependent on catchment size, including pre-channel and in-channel storage effects. In general, records from the most frequently gauged catchment range of 150-500 km<sup>2</sup> in area are preferred. This has the effect of providing a more precisely defined geographical distribution of run-off, since relatively generalised and integrated flows from the largest catchments are omitted (Ward, 1980).

(iv) Record length

There are several flow records of greater than 20 years duration available in Scotland, however most do not fulfill the conditions above. For the remaining data series, it is considered to be a methodological necessity to employ a standard "long term" reference period. In balancing further requirements of; (a) a long standard period; and (b) a representation<sup>ve</sup> range of data over the whole country; the 18-year period 1961-78 was adopted as the long term standard.

(v) Geographical location

In further pursuit of requirement (b) above, the final choice of records to be used was made by a more stringent application of the three initial criteria to select from alternatives situated in the same part of the country.



Ten gauging station records (Nos. 1-10) which satisfied the above conditions were selected, along with a further four records (Nos. 11-14) for areas where no wholly suitable data exist. The names of the gauging stations and rivers applying to the fourteen catchments shown in Fig. 2.10 are given in Table 2.2. Further details are provided in Appendix 2.

#### 2.4.2 Annual Pattern of Run-off

The annual run-offs in mm for the years 1970 to 77 inclusive are shown for the 14 gauged catchments on Fig. 2.11. As is indicated, 1973 was the calendar year of lowest run-off for the Borders, Lothians, Fife, Tayside and the eastern part of the Grampian Region. For most locations in these eastern areas, the annual run-off was typically one half to one quarter of the 1961-78 averages, which are shown on Fig. 2.11. The lowest 1973 run-off in relation to average occurred in easternmost parts, and in some small coastal catchments in East Lothian (not shown in Fig. 2.11), this figure was as low as 10%. For example, this percentage of estimated average annual run-off, corresponding to only 11mm, was recorded for the 26.2km<sup>2</sup> of the Peffer Burn West catchment measured at Luffness gauging station. (Forth River Purification Board, 1973). In eastern parts of the Highland Region, and all remaining areas represented on Fig. 2.11, 1972 was the year of lowest run-off during the 1971-76 period, except



FIGURE 2.9 : Duration of River Flow Records in Scotland  
Available in 1978

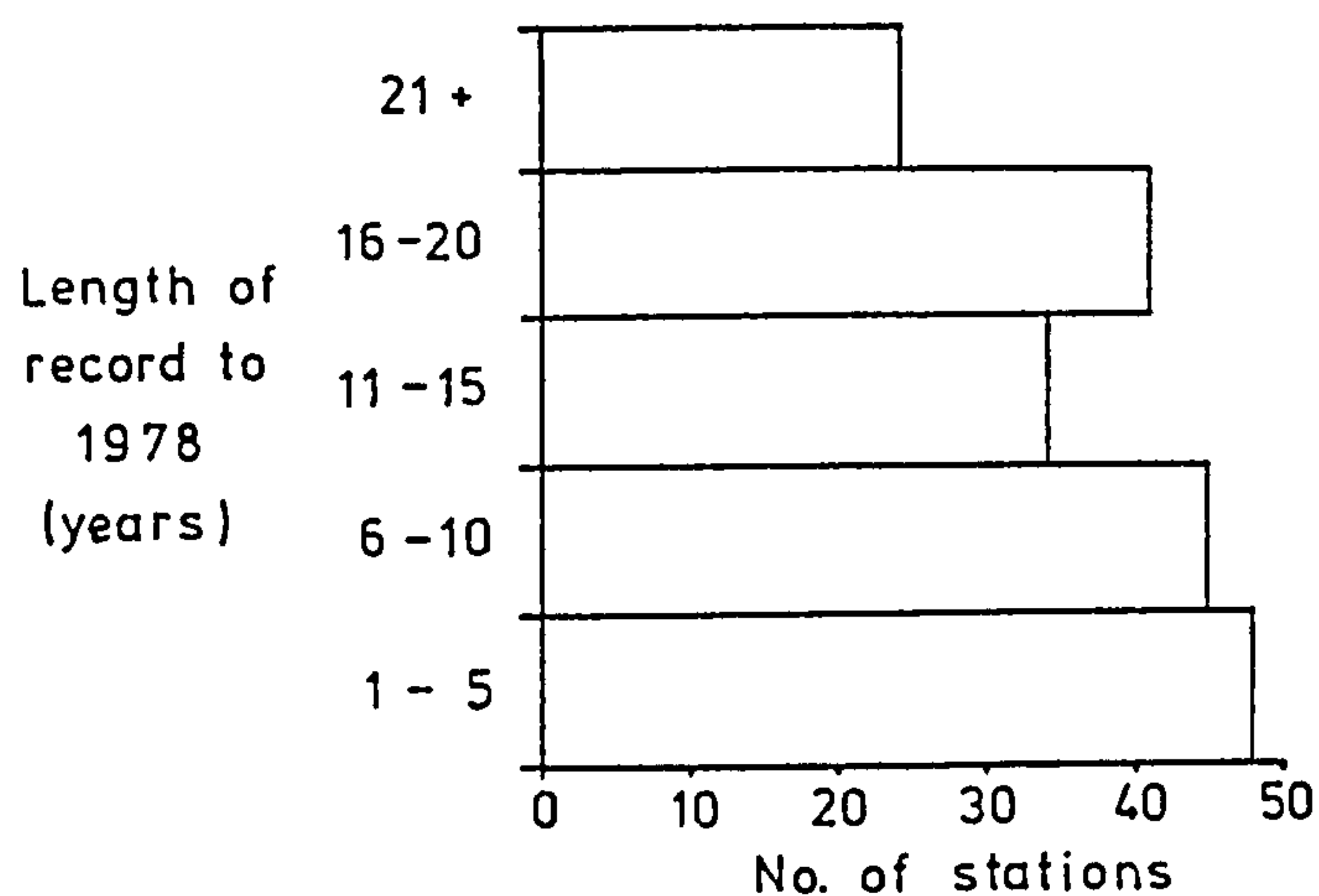


TABLE 2.2 : Names of Gauging Stations and Watercourses of  
Catchments in Fig. 2.10.

Ref. No. (Fig.2.10)	Gauging Station	Water- course
1	Balnaa	Dulnain
2	Avochie	Deveron
3	Woodend	Dee
4	Cookston	Dean
5	Glenochil	Devon
6	Craigiehall	Almond
7	East Linton	Tyne
8	Fairholm	Avon
9	Lyne Ford	Tweed
10	Hawick	Teviot
11	Halkirk	Thurso
12	Ardlethan	Ythan
13	Kemback	Eden
14	Friars Carse	Nith

**FIGURE 2.10 : The Locations of the Selected River Gauging Stations and Their Catchments (for further details see Table 2.2 and Appendix 2.2)**

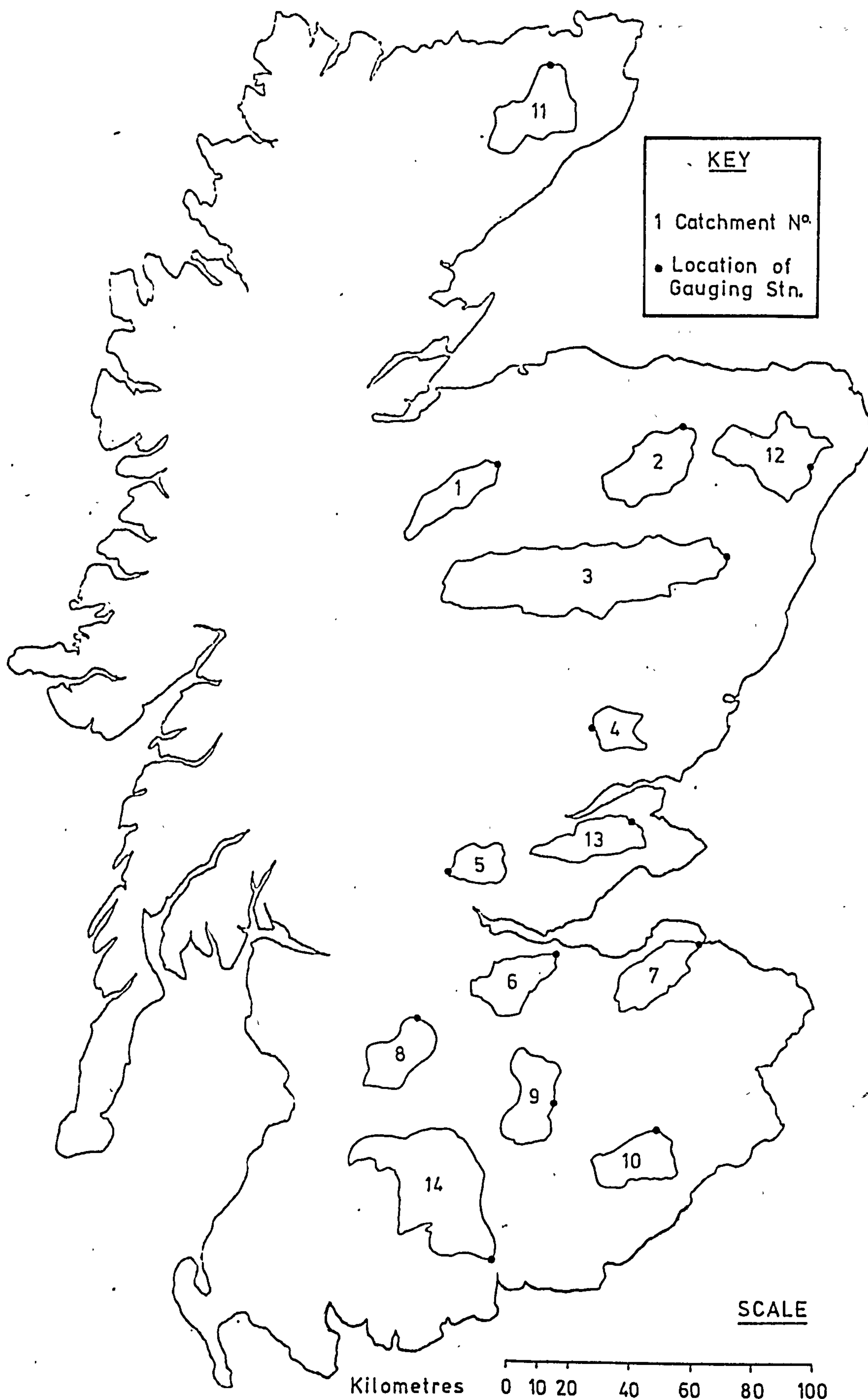
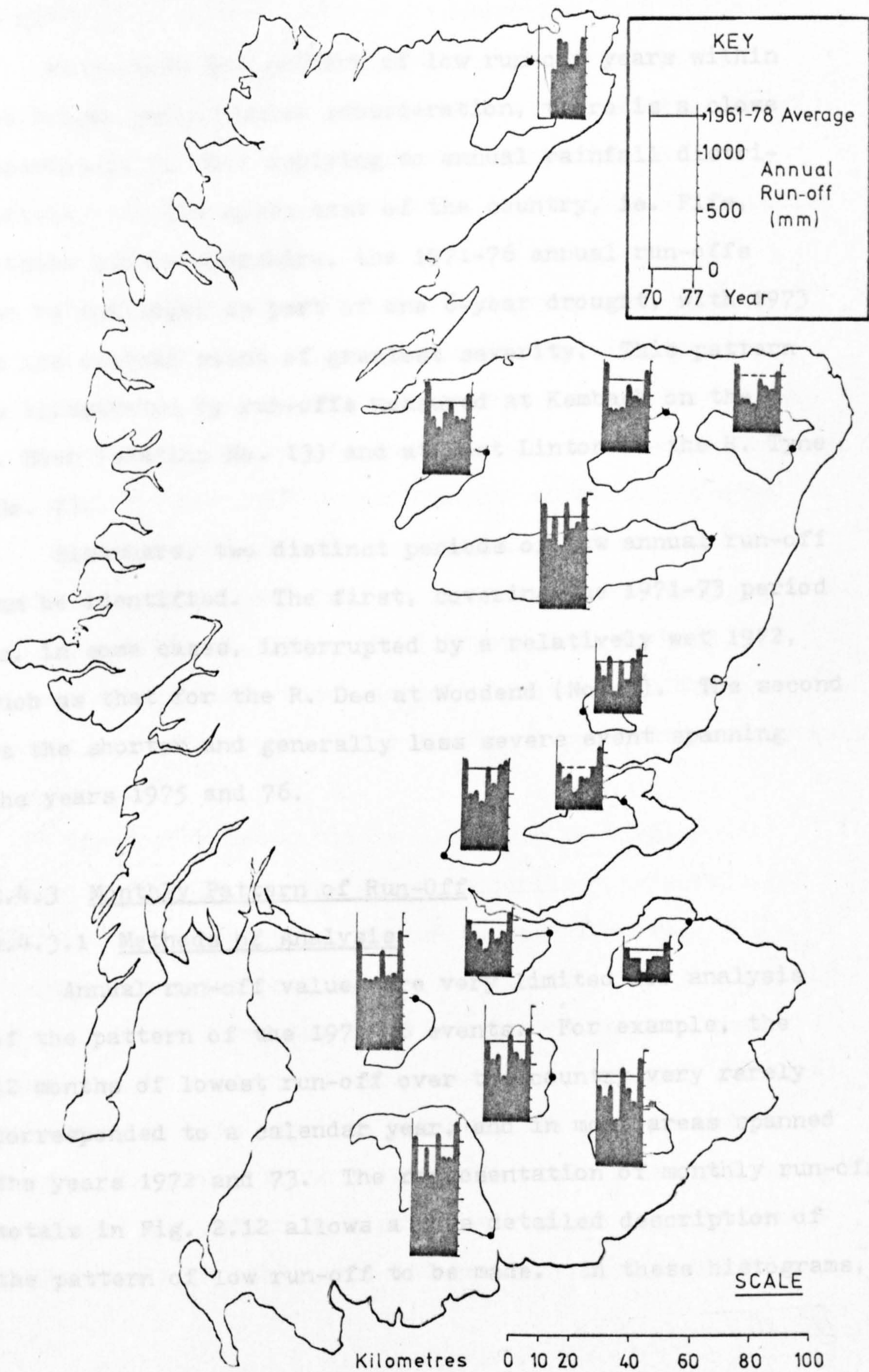




FIGURE 2.11 : Annual Run-Off for the Period 1970-77 for  
14 Selected Catchments





in the extreme south-west, where this distinction applies to 1971.

As regards the pattern of low run-off years within the 6-year period under consideration, there is a close resemblance to that applying to annual rainfall distributions. In the south-east of the country, ie. Fife, Lothian and Berwickshire, the 1971-76 annual run-offs can be envisaged as part of one 6-year drought, with 1973 as its central point of greatest severity. This pattern is illustrated by run-offs measured at Kemback on the R. Eden (station No. 13) and at East Linton on the R. Tyne (No. 7).

Elsewhere, two distinct periods of low annual run-off can be identified. The first, covering the 1971-73 period is, in some cases, interrupted by a relatively wet 1972, such as that for the R. Dee at Woodend (No. 3). The second is the shorter and generally less severe event spanning the years 1975 and 76.

#### 2.4.3 Monthly Pattern of Run-Off

##### 2.4.3.1 Methods of Analysis

Annual run-off values are very limited for analysis of the pattern of the 1971-76 events. For example, the 12 months of lowest run-off over the country very rarely corresponded to a calendar year, and in most areas spanned the years 1972 and 73. The representation of monthly run-off totals in Fig. 2.12 allows a more detailed description of the pattern of low run-off to be made. In these histograms,

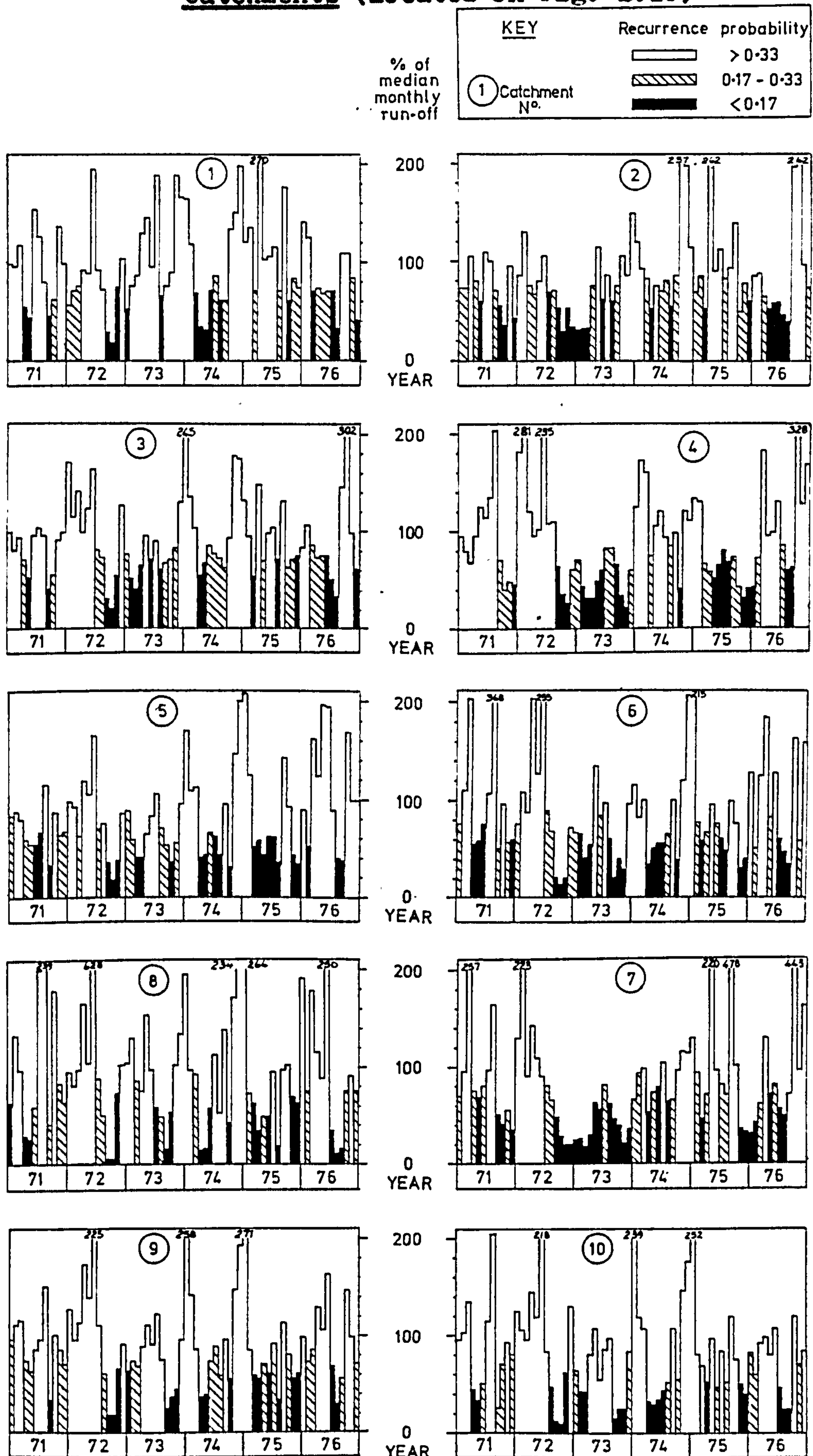


the percentage of the median monthly run-off (taken over the standard 18-year period) is shown for each month of the years 1971-76 inclusive. Although this type of treatment of a very seasonally variable parameter can be misleading, it does allow for some comparison of the deficiencies in run-off during different seasons, relative to "normal" events.

Further to this end, a rudimentary probability analysis (similar to that used in Section 2.3.2) is illustrated. Despite the fact that any percentile treatment of only 18 years of data will have severe limitations, it is considered that identification of monthly events of return periods of down to 6 years and from 6 to 3 years is acceptable. The corresponding recurrence probability intervals of, less than 0.17 and 0.17 to 0.33 respectively, allow some comparison between different monthly run-offs in the same location, and between different locations.

Firstly, however, it is necessary to examine the range of run-off for the given probability intervals for each month of the year. As can be seen from Fig. 2.13 (representing the probability distributions of low monthly run-off in mm), for all locations shown, the low end variation in winter and autumn months is greater than that in summer in both absolute and relative (to the median) terms. Moreover, it is notable that this increased variation in winter and autumn is greater over those run-off levels associated with the lowest levels of probability. These

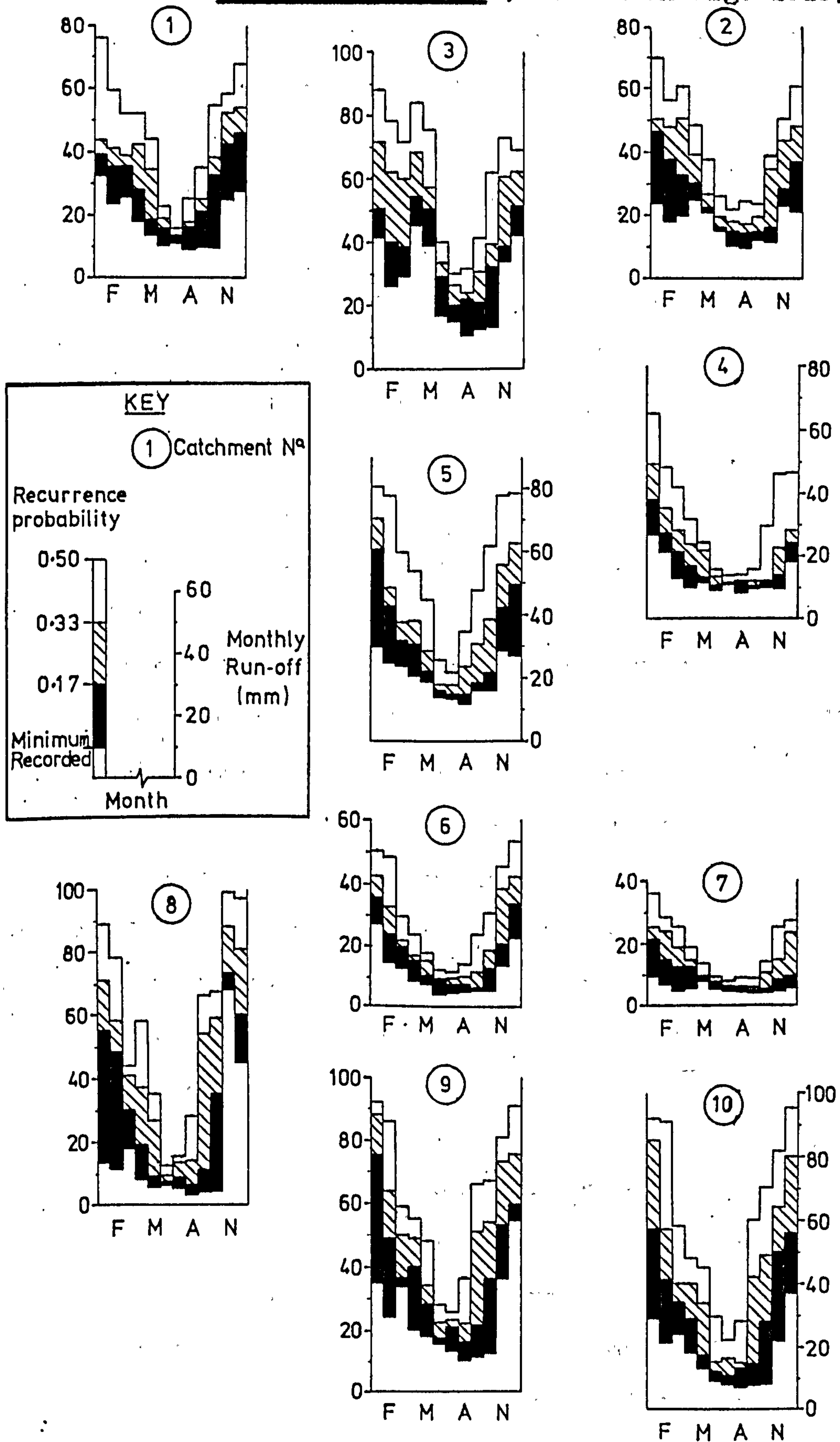
**FIGURE 2.12 : The Percentage of Median Values, and Annual Recurrence Probabilities, of Monthly Run-Off Events During the 1971-76 Period for 10 Catchments (located on Fig. 2.10)**



Note : the juxtaposition of the data for catchments on this figure represents their relative geographical positioning



**FIGURE 2.13 : Long Term (1961-78) Probability Distributions of Monthly Run-Off Events Below Median Values for 10 Catchments (located on Fig. 2.10)**



Note the juxtaposition of the data for catchments on this figure represents their relative geographical positioning

features are demonstrated by the ranges over which monthly run-offs of a recurrence probability of 0.33 to 0.17 , or less than 0.17 take place . Such ranges are hatched and black respectively in Fig. 2.13. Thus, for a given percentage (less than 100) of monthly median run-off, the corresponding recurrence probability for a summer month will be less than that for an autumn or winter month. For example, at East Linton (No. 7), an event corresponding to 60% of monthly median run-off has an annual recurrence probability of less than 0.17 for each of the months April to July inclusive, and of 0.17 to 0.33 for all other months.

In general, all the histograms in Fig. 2.13 representing the recurrence probabilities of monthly run-off levels, which are less than median values, and which are based on an 18-year period of record, depict the expected seasonal run-off regime for their relevant locations. However, in the one example where this is clearly not the case, ie. the months of October to December at Fairholm on the R. Avon (No. 8), care must be taken in assessing the monthly pattern of the events of the 1971-76 period.

#### 2.4.3.2 Seasonal Nature of Low Run-Off Spells

As Fig. 2.12 clearly illustrates the distribution of individual low run-off months is complicated both in terms of its temporal, and geographical variation. If, however, more sustained periods of abnormal run-off such as those lasting for say 3 or more months are considered, then geographical patterns become more apparent. On this basis,



three main spells of low run-off can be identified as follows.

The first and longest spell of reduced run-off concerns the 1971-73 period. In the north-east, eg. at Avochie (No. 2), this spell could be said to have begun at the start of 1971. However, monthly run-offs became exceptionally low in July 1972 as they did over the whole country. This run of events ended earlier in the west, eg. in November 1972 at Fairholm (No. 8), then in March 1973 at Balnaan (No. 1). Over the majority of the eastern part of Scotland this low run-off period ended in November or December 1973. However, in the extreme south-east, as shown by the run-off at East Linton (No. 7), this event continued until October 1974. Indeed, at this location a period of 24 consecutive months of less than median run-off ended on this month.

The second well-defined low run-off period beginning in March or April 1974 is evident at all locations, except Cookston (No. 4), and East Linton (No. 7) where the previous spell was still apparent. Once again, this spell was of shorter duration in the west, and lasted for only 3 months at Fairholm (No. 8). In the east this spell continued, sometimes at a reduced level of severity, until September or October of the same year.

The third and final period of sustained low run-off occurred over the last two years of the period under concern. In central and southern districts, February or March 1975

marked the commencement of this spell, as is shown at eg. Fairholm (No. 8), Glenochil (No. 5), and Lyne Ford (No.9). To the north-east (Avochie (No. 2) and Woodend (No. 3) ) this event began in October 1975, and in the south-east (East Linton (No. 7) ) one month later. In the northernmost catchment on the R. Dulnain at Balnaan (No. 1) the initiation of this spell was further delayed, until March 1976.

Once again, further repetition of the geographical distribution of the duration of the two previous events is evident. That is, western districts saw the end of this low run-off spell markedly earlier than those in the east. Whilst at Fairholm (No. 8) this event ended in December 1975, in the more easterly central locations (eg. Glenochil (No. 5), Lyne Ford (No. 9), Cookston (No. 4) ), it continued until February or March 1976. In those areas of later commencement, the ending was similarly displaced, such that in the Grampian region in the north and the eastern parts of the Borders and Lothian in the south-east, September 1976 was the final month of a sustained period of low run-off. However, in this case, unlike the previous two, the duration of this period was not markedly longer in the east than it was in the more western parts of Scotland.

Apart from the durations of such spells, their seasonal nature is of notable interest. In the first, the initiation was in late summer and the end in autumn, in most cases. The much shorter 1974 event shared the same ending point,



although it commenced in spring. Also ending in the autumn was the 1975/76 event for those eastern locations when the low run-off spell commenced in the autumn of the previous year. Thus, in the more severely affected eastern half of the country, the three drought periods lasting for typically 12-24, 6 and 12 months ended in the autumns of 1972 or 73, 1974 and 1976 respectively.

#### 2.4.4 Low Flows During the 1971-76 Period

##### 2.4.4.1 Methods of Analysis

The five measurable factors of hydrological drought identified earlier have been assessed in general terms, on the basis of monthly and annual run-off. The matter of "low flows" however is more complicated, and requires methods of analysis other than those outlined at the beginning of this section. Since in Scotland there are typically large seasonal differences between river flows, it is rather inappropriate to describe short duration low flows as deviations from, or percentages of annual averages. Even to analyse low flows on a seasonal or monthly basis could provide misleading results. As has already been indicated by Fig. 2.13, low flow variation is generally much greater in winter than in summer, in both absolute and relative terms. Thus, it is more usual to describe low flows in terms of probability. However, there is a proliferation of such measures, for which the Institute of Hydrology (1978) identify the following three explanations;



(a) different definitions of a low flow event, in e.g. terms of discharge, volume or recession rate;

(b) different methods of expressing frequency ie. in different units of time;

(c) different duration time units of low flow, ranging from the instantaneous to a number of days or months.

This report then goes on to list and discuss the major methods of analysing low flows, these being;

- (i) Flow Duration Curve;
- (ii) Flow Frequency Curve;
- (iii) Low Flow Spells;
- (iv) Storage Yield Analysis;
- (v) Recession Behaviour;
- (vi) Base Flow Index.

The merits and disadvantages of the first and most commonly used three are now considered in turn.

(i) Flow Duration Curve

This describes the relationship between a given discharge and the percentage of time during which it is equalled or exceeded, based on daily or multi-day periods. Its method of construction is detailed by both Searcy (1959) and Hoyle (1963).

The most important feature of its application is that it can include some measure of "demand", or eg. "Minimum Acceptable Flow" (Boulton, 1965), pertaining to a river system. For example, a sewage effluent discharge operation

may be designed to be optimally effective when the diluting river flow equals or exceeds a certain level whose probability of occurrence is known (eg. 95% and 99% exceedence flows are commonly quoted in such instances). The use of a Flow Duration Curve allows examination of how often such a "demand" is satisfied.

However, its major limitation is its lack of continuity, ie. no indication is given as to the temporal distribution of different flow levels.

(ii) Flow Frequency Curve

Using the method described by Riggs (1968), such a curve allows the prediction of the return period (in years) of a river's flow falling below any given level, over a set duration of eg. 1 day to 180 days. This technique has similar applications to that above, however it is perhaps less "demand" orientated, in that the basis for calculation is the chosen time period rather than the discharge. In its favour, it does contain an element of continuity, although the variation of flow within the chosen time period is not considered.

(iii) Low Flow Spells

This methodology involves the examination of; (a) "deficit durations", defined by the Institute of Hydrology (1978) as the spell over which river flow is below a given "demand" threshold; and (b) "deficit volumes", which accrue over this spell. The same report suggests two ways of

expressing these spells and volumes, the first being the frequency of occurrence of an event, and the second, the proportion of years in which a given spell or volume is exceeded.

Thus, this method which can involve a "demand" or threshold feature has the added advantage of the inclusion of the possibility of assessing the distribution and grouping of low flow events. Such information concerning the frequency of flows being below a threshold value for given periods could be of much importance for the management and planning of say, a sewage effluent discharge operation on a river

The three remaining methods for low flow analysis are rather specialised in nature to be considered at this juncture, however their applications are discussed later where relevant.

Ideally, a comprehensive low flow investigation would include all three of the techniques discussed in detail. However, consideration of the vast amounts of data which would require processing renders this option outwith the realms of this study. Consequently, the method of analysis which provides the most useful information, with regard to time spent, was chosen, ie. the Flow Duration Curve. In general, records of daily mean flows kept at River Purification Board offices were most suited to this type of investigation.

#### 2.4.4.2 A Flow Duration Analysis Made on an Annual Basis

The following Flow Duration Analysis has two main



objectives, ie. to;

a) describe variations in flow on a daily time base;  
and b) compare the incidence of low flows of different probability levels.

Flow Duration Curves, based on daily mean flows, were derived using the method of Searcy (1959). This was done for catchments No. 1 to No. 10 in Fig. 2.10, except the Dee at Woodend (No. 3), for the reason stated in Section 2.4.1. Tabulated summaries of such curves for the adopted "long term" standard period of 1961-78, and for each of the years in the 1971-76 period are given in Appendix 4.

Although it is customary to use "percentage exceedence flows", it is perhaps more fitting and relevant, when concerned with low flows to refer to flows which are not reached for a given percentage of time. These could suitably be named "percentile flows" in much the same way as Maher (1968) analysed rainfall. Thus, for example, a 95% exceedence flow corresponds to a 5 percentile flow.

The possible limitations of the following percentile flow analysis should be mentioned prior to further discussion. The major shortcoming concerns the possible bias added to the relatively short 18-year standard period percentile flows by the 6-year (1971-76) low flow spell which is included in it. However, since this would most likely lead to an underestimation of flows of given percentile values, the abnormality of events of 1971-76 will tend to be under rather than over estimated.

The histograms in Fig. 2.14 show for each year of the 1971-76 period the percent of daily mean flows for

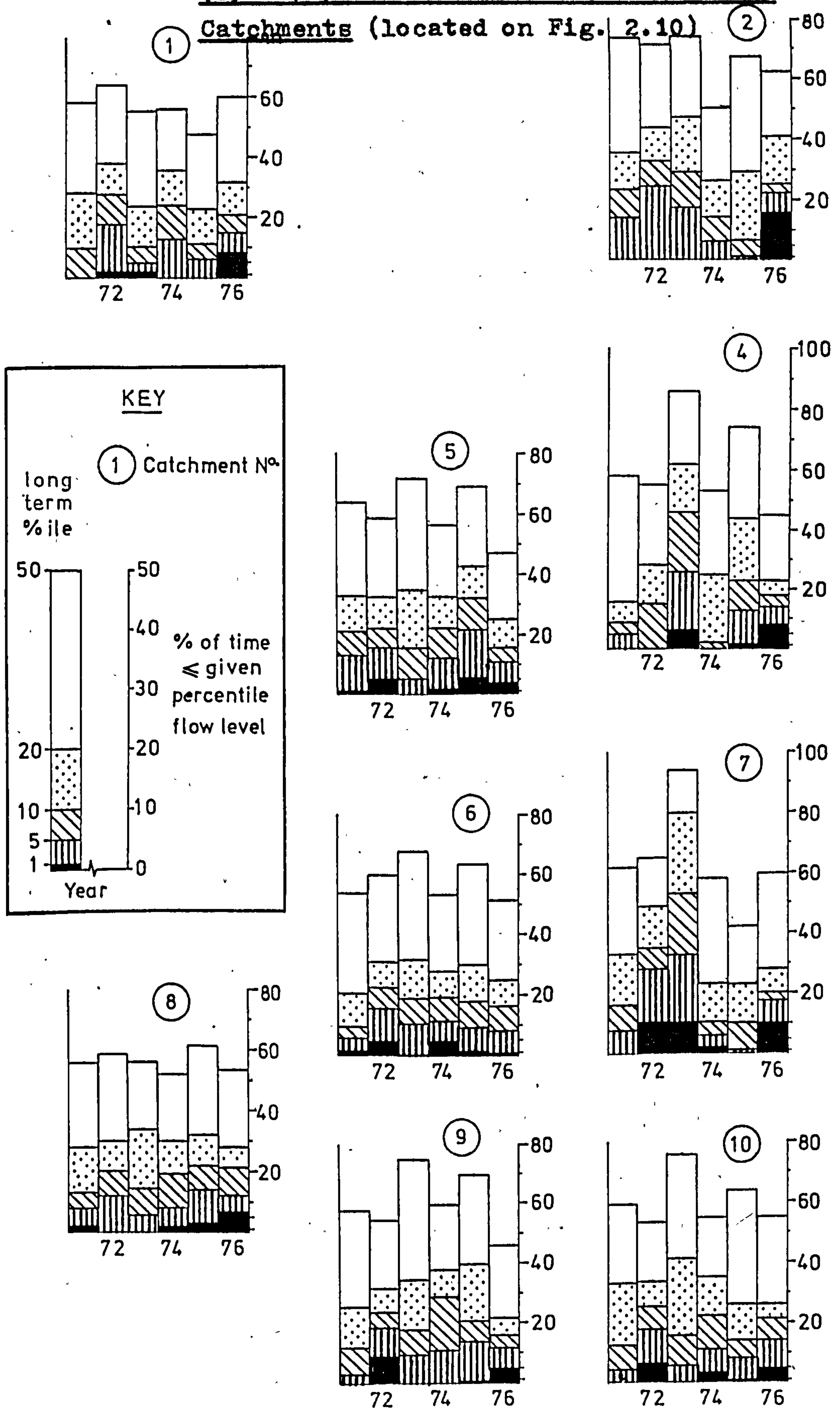
which flow was less than or equal to given "long term" percentile levels, ie. 50, 20, 10, 5 and 1. Consequently, comparisons of the increased or diminished incidence of flows of a given long term probability level can be made. Such comparisons can be readily made between different years and different locations, since this probability-based analysis provides a relative measure of the occurrence of given flow levels.

These considerations are made in the following discussion, which is intended to reveal further hydrological characteristics of the three major low run-off periods identified earlier. The first such period, which involves various durations spanning the years 1971 to 73, typically involved the highest incidence of flows less than the 50 percentile, although perhaps less so in the most western catchments (at Balnaan (No. 1) and Fairholm (No. 8). Indeed, the year 1973 contained the greatest number of daily mean flows less than median values for all locations except these two above. The range was from 72.5% of the time at Glenochil (No. 5) to 94% of the time at East Linton (No. 7). In the easternmost catchments, measured at Avochie (No. 2), Cookston (No. 4), Craigiehall (No. 6), East Linton (No. 7) and Hawick (No. 10), the years 1972 and 73 between them had the highest rates of incidence of all low percentile flows illustrated, except for the 1 percentile at the first two locations mentioned.

The second sustained period of low run-off, included in the year 1974, affected most areas to a very similar



FIGURE 2.14 : Annual (1971-76) Incidences of Given Long Term (1961-78) Percentile Flow Levels for 9



Note : the juxtaposition of the data for catchments on this figure represents their relative geographical positioning



degree. Thus, whilst the levels of severity of the events of the previous three years was continued in the west, a relative easing of the high incidence of low flows was experienced in the east. For example, whilst the incidence of the 20 percentile flow or less, was continued at around 30% of the time at Fairholm (No. 8), it fell from 50% in 1973 to 24% of the time in 1974 at East Linton (No. 7).

During the last low flow period, occurring in 1975 and 76, in those central and southern areas where the low run-off started earlier in 1975, there is a markedly high incidence of daily flows less than median (or 50 percentile) values. This is shown for eg. Glenochil (No. 5) and Fairholm (No. 8). The incidence of all low flow levels was generally not higher than those attained in previous years, except at the former location above. For the year 1976, all the sample catchments (except that measured at Craigiehall (No. 6)) experienced a very high frequency of flows equal to or less than the 1 percentile level. Indeed, at Avochie (No. 2), which is the most extreme example, such flows occurred on 16% of days over the year. In the north and west, the 1976 incidence at this 1 percentile level was greater than in 1972 or 73, but in the south and east, was of approximately similar proportions to these earlier years. Overall, the duration of low flows over 1976 was of relatively decreasing severity towards the higher percentile flows; so much so that the frequency of flows less than median values was often less than 50%.

The frequency range was 45% (Cookston, No. 4) to 62% of the time at Avochie (No. 2).

#### 2.4.4.3 Comparison of Flow Events at Different Percentile Levels

Although the foregoing Flow Duration Analysis has facilitated relative assessment of hydrological drought between different years and different locations, there remains one major shortcoming. This is associated with the comparison of the relative severity of the increased (or decreased) incidence of one particular percentile flow against that of another, for a given location. For instance, Fig. 2.14 shows that during 1973 at East Linton (No. 7), the daily mean flow was less than the long term median flow for 94% of the time, whilst the 1 percentile flow or less, occurred proportionally 10 times more than for the long term situation. It would be very useful to be able to make a comparison of the severity of these two unusual hydrological events.

Of course, actual use of, and demands made on, a river will have a major influence on the assessment of the comparative severity of such events. However, if at this stage, such considerations are ignored, then an initial comparison, concerned with the "supply" element of drought, can be made. This can be made on the basis of a probability analysis based on a series of annual events. An understanding of relevant recurrence probabilities would make



Flow Duration information more useful, in that some measure of the temporal distribution of events over the long term is included, albeit on an annual basis.

A rudimentary analysis along the above lines is shown for data from East Linton (No. 7) and Avochie (No. 2) in Figs. 2.15.1 and 2.15.2 respectively. The frequency of occurrence of flows less than or equal to stated percentile values was calculated and ranked for each of the 18 years of record. Plotting positions were determined using Wiebull's (1939) method. Since only 18 samples of durations of given percentile flows are available (fewer for rarer flow levels), this was considered to be too few to fit a precise probability curve. For example, Riggs (1968) suggests that a sample of even 20 to 30 hydrological variables may be insufficient to derive a reliable frequency curve. More specifically, when investigating the somewhat similar "Low-Flow Frequency Curves", based on 28 to 60 years of records, Hardison and Martin (1963) experienced "the difficulty of finding a type of statistical distribution that would fit the data for all lengths of period at every station".

The type of analysis here has not been presented before, and as no obvious choice of statistical distribution is apparent, it seems reasonable to adopt the simplest one which provides a reasonably good fit for the available data. Thus, a normal or Gaussian distribution was assumed. Since this distribution ignores the possibility of skewness, a feature often associated with hydrologic



FIGURE 2.15.1 : Recurrence Probabilities of Annual Durations  
of Given Percentile Flow Levels at  
East Linton on the R. Tyne

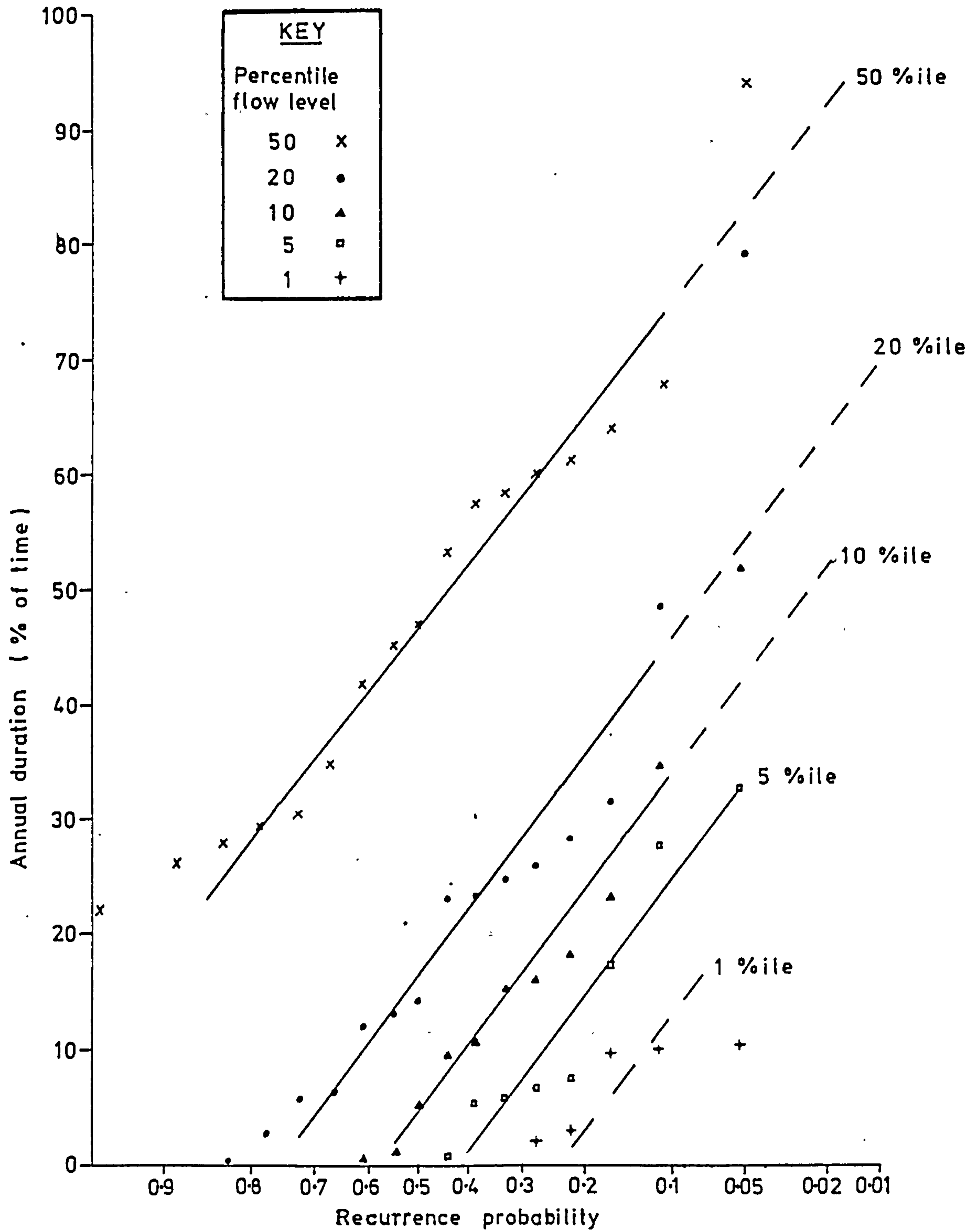
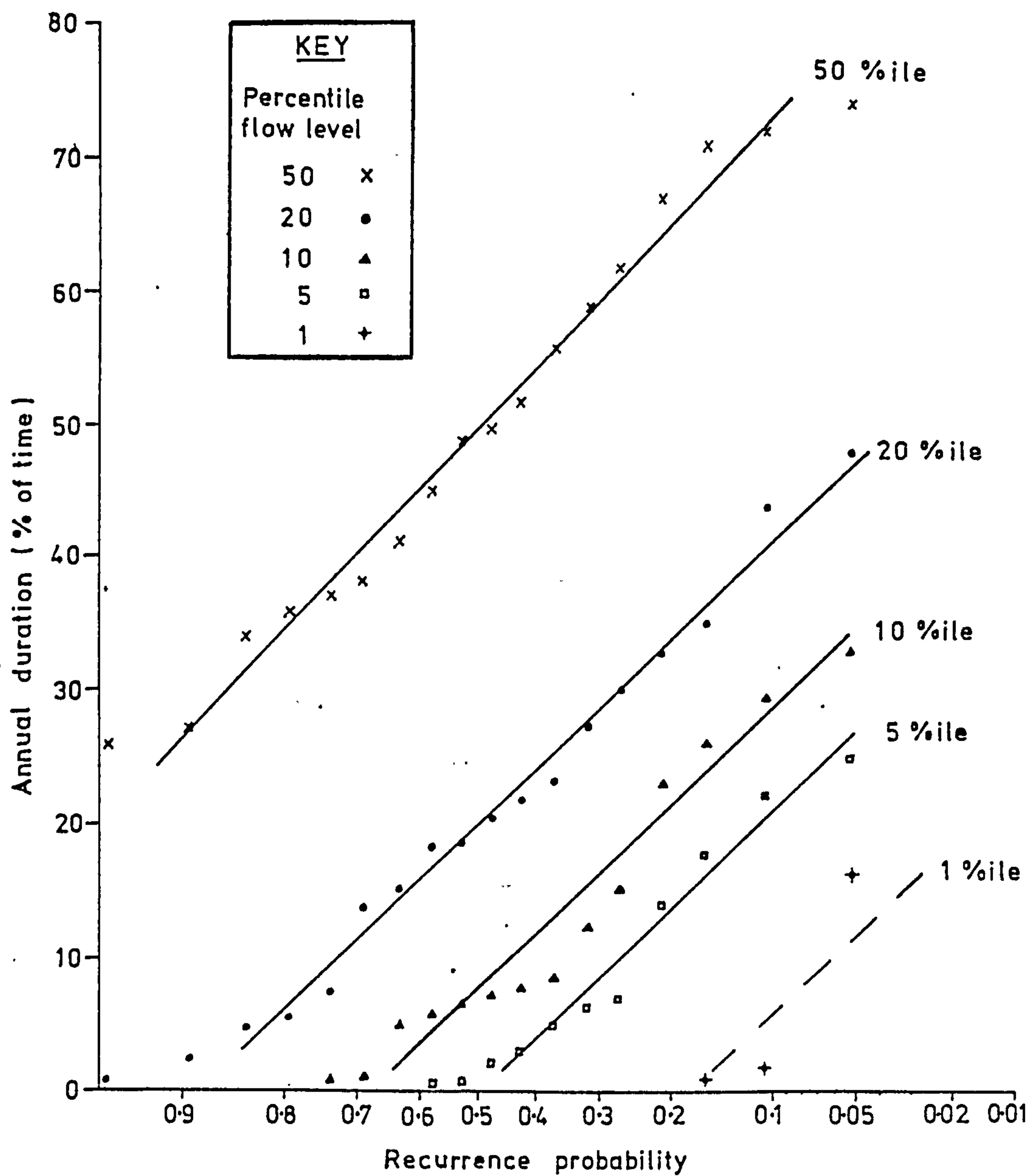


FIGURE 2.15.2 : Recurrence Probabilities of Annual Durations  
of Given Percentile Flow Levels at Avochie  
on the R. Deveron



distributions, then annual recurrence probabilities, especially those concerned with extreme events, cannot be estimated with much confidence.

The plots of probability on Figs. 2.15.1 and 2.15.2 each produce a series of near-parallel lines corresponding to the 50, 20, 10, 5 and 1 percentile flow levels. The 1 percentile lines however, with only 5 and 3 points respectively available for their resolution, are ill-defined. In most cases, the actual distributions seemingly correspond closely to the normal distribution, given by a straight line on this scale. There is some evidence of skewness in that the low-duration end of the curves tend to "flatten out" from the foregoing straight-line relationships. At the other, more relevant, end of the distributions there is no consistent evidence to suggest a pattern of skewness.

The recurrence probabilities of the annual durations of flow less than or equal to given percentile values occurring in the most extreme year of the 1971-76 period tend to be very low, as Table 2.3 illustrates. Indeed, in most cases, the estimated probabilities of recurrence are well outwith the range of the data base (down to 0.055). Unfortunately, this renders the reliable estimation of such probabilities impossible, but does not prevent some relative comparison between events, based solely on rank.



TABLE 2.3 Estimated Recurrence Probabilites of the  
Longest Duration Annual Percentile Flow Events  
of the 1971-76 Period at East Linton and Avochie

Percentile flow Level	East Linton		Avochie	
	Year	Recurrence Probability	Year	Recurrence Probability
50	73	0.016	73	0.090
20	73	0.004	73	0.047
10	73	0.021	72	0.063
5	73	0.053	72	0.065
1	73	0.120	76	0.030

For example, for the R. Tyne at East Linton, the severest annual event, in terms of probability, was the 290 days (79.5% of the year) of flow less than or equal to the 20 percentile level in 1973. In the same year, the duration of 1 percentile flow would seem to have been the least improbable of the events considered above. On the other hand, on the R. Deveron at Avochie, the 1976 duration at this percentile level is arguably the outstandingly abnormal annual event over the 1971-76 period.

Other more general, but very relevant hydrological features of the drought period, and their expected impacts

on human activities are now summarised for the country as a whole.

#### 2.4.5 Summary of Important Hydrological Features

The problems associated with the analysis of a low run-off event have been recognised. In the general context these are mostly concerned with the fact that no single analytical technique adequately covers all aspects of hydrological drought. Several approaches, including one new development, have been employed to overcome this problem. A more specific difficulty associated with this study is that of estimating the recurrence probabilities of the extreme events of the 1970's from a data base of very limited duration. This shortcoming is given detailed attention in Section 2.6.

The major drought spells in relation to river flows have been identified as that of 1971-73, and of 1975-76. The former period is particularly notable for its long duration, and the fact that it was progressively more severe and longer from west to east. Two notable examples are provided by; the R. Deveron at Avochie in the north-east, where the run-off in each year of the 1971-73 period was less than 65% of the long term average; and in the south-east by the R. Tyne at East Linton, where 31 months of less than average monthly run-off were centred around the year 1973. This year in the south-east was perhaps the most hydrologically abnormal on record anywhere

in Scotland. For example, during this year at the latter location above, 94% of all daily flows were less than the long term median value.

The period of low run-off during 1975 and 76 is most notable for the extremely low flows experienced during July and August of the latter year, which were experienced over the whole country. In the south, these events were on a par with those of the preceeding years, but in the north-east many rivers, eg. at locations 2, 3 and 12 on Fig. 2.10, experienced their lowest recorded flow. At Avochie on the R. Deveron (No. 2), flows were lower than in any year before for 55 consecutive days in the summer of 1976.

The specific hydrological nature of these low run-off events can be associated with particular potential water resource management problems. The duration, of around 3 years, and severity of the earlier event can be especially linked with likely problems for the management of water supply sources where some form of storage is involved. For example, impounding reservoirs depend on annual periods of sufficient run-off at the required time to recharge summer season depletions. Difficulties could be expected to be particularly severe in that in the east of the country, the periods of low run-off from 1971 to 73, (74 in some cases) tended to end in the Autumn or early Winter. Usually, just before this time of the year, and earlier still during a sequence of dry years, reservoir levels tend to require refilling from their seasonal low,



and hence are at their most vulnerable to running dry.

Potential problems associated with the short, but severe low flows of the summer of 1976 (and similar ones in proceeding years), could be expected to apply to those water uses which do not involve storage, but are dependent on "the run of the river". For example, water supplies obtained directly from river abstractions would be most vulnerable to this type of hydrological drought. The actual impacts suffered and the responses of water authorities are detailed in Section 3.

Recorded flows during extreme events such as those of 1976 yield valuable information concerning the natural variability of water availability, but only for gauged catchments. For much of the land area of Scotland, only limited information is readily available which would allow the calculation of probable low flow levels, for example, in the form of percentile flows, which could be used as a basis for water resource management decisions. The following pages present the methods used, and results obtained for an exercise aimed at producing detailed maps of 1 and 5 percentile run-off levels throughout eastern Scotland.

## 2.5 GEOGRAPHICAL VARIATION OF LOW FLOW YIELDS

So far, the flow duration investigation of run-off

has been centred on ten sample catchments for which adequate long term data exist. Although this analysis has allowed a representation of the geographical distribution of the incidence of low flows, the actual quantities of water involved have not, as yet, been presented. Thus, it was considered to be very useful to construct a map of the study area (eastern Scotland), depicting actual flow rates corresponding to given percentile values. Such information could be used in conjunction with that on Fig. 2.14 showing the regional incidence of 50, 20, 10, 5 and 1 percentile flows for each of the 6 years in the 1971-76 period. In addition, an areal assessment of low flow yield could provide significant data for the planning and management of water resources, especially in areas where such information is limited.

### 2.5.1 The Estimation of Low Flow Yields

#### 2.5.1.1 Previous Studies

One recent study involving an areal assessment of low flow yields was made by the Institute of Hydrology (1978). On the subject of estimates made for ungauged sites, they quote the supportive evidence of Thomas and Benson (1970) and Chang and Boyer (1977) in discussing the various difficulties involved. As a result, the need for a factor describing the effects of ground water geology is recognised as a necessity. Hence, the report cited suggests a procedure

for estimating such flows based on average annual rainfall (SAAR) and a "base flow index" (BFI). This latter component is measured from "nearby gauged catchments and a knowledge of the solid and drift geology of the catchment".

For central and northern Scotland, the generalised equation for low flow derivation is,

$$Q_{95(10)} = 7.60\sqrt{\text{BFI}} + 0.0263\sqrt{\text{SAAR}} - 1.46 \quad \dots\dots 1$$

where  $Q_{95(10)}$  represents the 95 percent exceedence flow for time units of 10 days (in  $\text{ls}^{-1}\text{km}^{-2}$ ).

For mid and east Lothian, the Borders, Dumfries and Galloway and the south-west of Strathclyde the relevant equation is slightly different, ie.

$$Q_{95(10)} = 7.60\sqrt{\text{BFI}} + 0.0263\sqrt{\text{SAAR}} - 1.84 \quad \dots\dots 2$$

There is also a simple generalised relationship which can be used to convert  $Q_{95(10)}$  into 95 and 99 percent exceedence (5 and 1 percentile respectively) one-day discharges.

#### 2.5.1.2 Derivation of 1 and 5 Percentile Flows

As an alternative to such generalised empirical formulae as those above, it was decided to attempt to derive maps of 1 and 5 percentile flows using only actual gauged discharges. This was made possible by the fact that considerable quantities of data concerning "spot gaugings" were found to exist at various River Purification Board Offices.



The method of analysis employed was as follows.

Firstly, flow data were divided into 3 categories, ie;

- (i) those of gauging stations where daily records covered the 1961-78 standard period;
- (ii) those where gauging station records spanned only part of this period;
- (iii) those for locations where only isolated spot gaugings existed.

For the first set of records, 1 and 5 percentile flows were derived from 18-year Flow Duration Curves by the method referred to in Section 2.4.4.2. An example is provided by Fig. 2.16.1, for the River Teviot at Hawick (the 323 km<sup>2</sup> catchment is No. 10 in Fig. 2.10), in the Tweed River Purification Board area. Plotting of the flow duration data such as that tabulated in Appendix 4, allows the partial curve represented in Fig. 2.16.1 to be drawn, and the flow values at the 1 and 5 percentile levels (2.3 and 3.2 l s<sup>-1</sup> km<sup>-2</sup> respectively in this case) to be read off.

For the second category of river flow records above, these percentile flows were derived using the method of Searcy (1959). In this technique, a relation is established between the station under consideration and an "index" station (generally the nearest long term station), for the period of concurrent record. This is then taken to represent the relationship between flows over the long term period, and thus long term percentile flows can be estimated for the short record station. An illustrative example is provided by Fig. 2.16.2, where the relationship

of flows over the concurrent period of record from 1972 to 1978 for the short term station at Jedburgh on the Jed Water (catchment area  $139 \text{ km}^2$ ), and its index station 15 km to the east at Hawick on the R. Teviot is shown. Using the long term 1 and 5 percentile flows of 2.3 and  $3.2 \text{ l s}^{-1} \text{ km}^{-2}$  respectively obtained from Fig. 2.16.1, the curve in Fig. 2.16.2 provides long term estimates of 2.3 and  $2.9 \text{ l s}^{-1} \text{ km}^{-2}$  respectively for these flow levels at the short term station. The above procedure assumes that the frequency of occurrence of given low percentile flows is the same for both stations over both the short and long term periods. For pairs of closely-situated, or adjacent catchments, as is generally the case in this study, this seems reasonable as they will be influenced by climatic events of similar probabilities.

One particular difficulty arose concerning the situation in the far north. The longest running gauging station in the area, at Halkirk on the R. Thurso (see Fig. 2.10, No. 11) is a considerable distance (100km) from the nearest catchment with a long term station. Indeed, three such catchments are approximately equidistant from that on the R. Thurso. Consideration of this distance makes the assumption of a similar distribution of flow over the entire common 7-year period untenable, and inspection bears this out. However, a period of monthly rainfall of similar recurrence probability over the relevant areas was identified, ie. the summer of 1976. The relation found between the Halkirk data and that for the R. Deveron



at Avochie for this period was discovered to be the most successful. Consequently, flows over this 4 month period were used as the basis for an estimation of long term 1 and 5 percentile flows for the short record station.

For the third group of flow data, another technique of Searcy (1959), as condensed by Hunt (1963), was employed. Here, the corresponding percentile flow on the same date, at a nearby gauging station (of either category (i) or (ii) above) is used to plot the percentile level of a spot gauging at another site. Thus, as well as assuming similar long term frequency distributions of climatic events likely to result in low percentile flows for nearby catchments, this technique also assumes the simultaneity of precisely defined percentile flows. Consequently, it is subject to error associated with the variability of particular characteristics between individual catchments, such as flow recession behaviour.

However, Hunt successfully used 9 such pairs of gaugings to estimate the flow duration behaviour at a normally ungauged site. The Institute of Hydrology (1978) suggest the use of at least 10. Since this analysis is concerned only with the extreme low flow end, however, it was decided that a minimum of 3 gaugings could be employed. Spot gauged sites which did not fulfill this condition, or for which either no sensible relationship could be found with the index station, or whose gaugings fell outwith the 1 to 5 percentile range were excluded.



FIGURE 2.16.2 : Use of the Relation Between Flow Duration Curves (1972-78) for the R. Teviot at Hawick and the Jed W. at Jedburgh to Estimate Long Term 1 and 5 Percentile Flows at the Latter

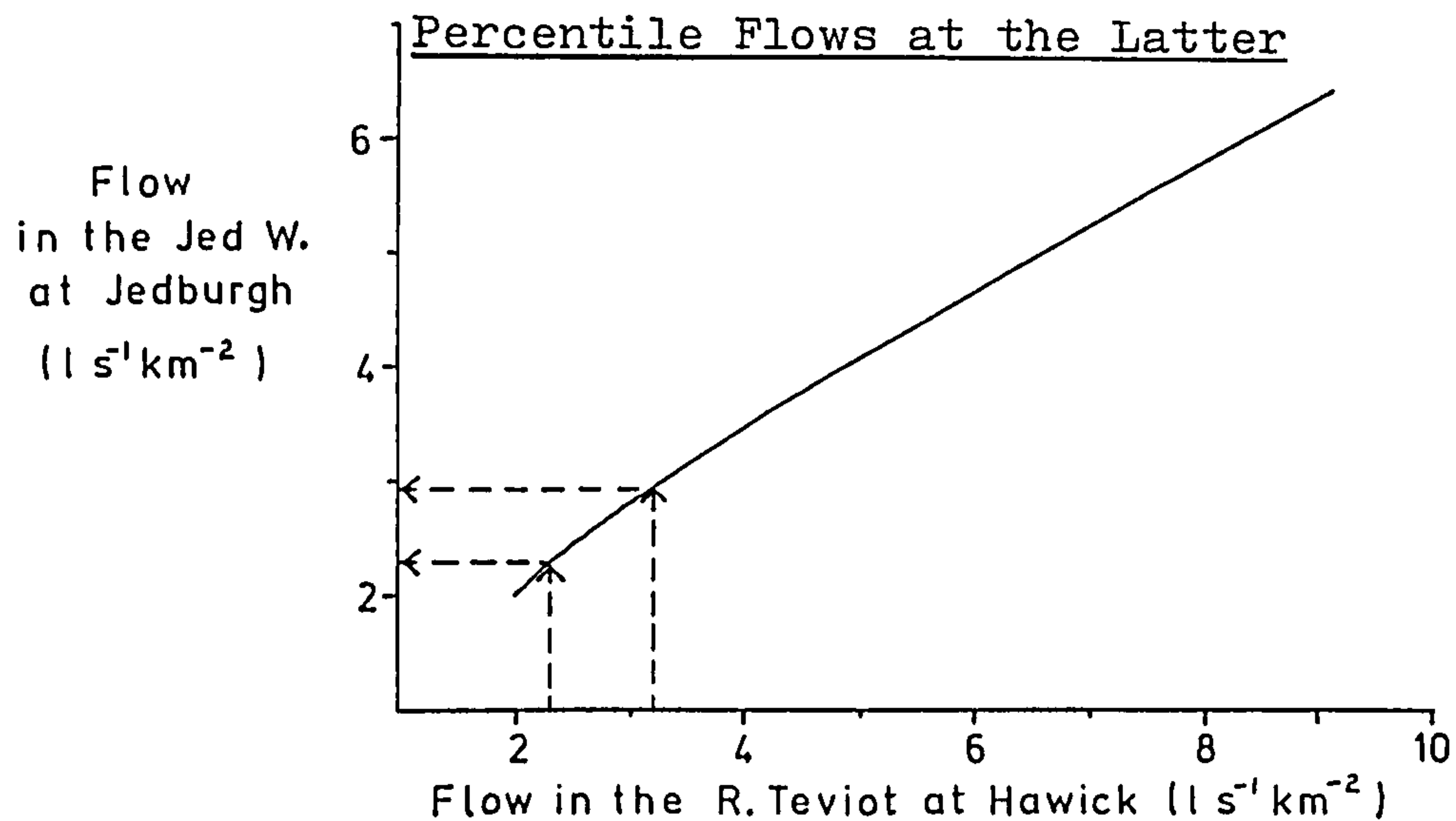


FIGURE 2.16.1 : Long Term (1961-78) Flow Duration Curve for the R. Teviot at Hawick for Flows up to the 20 Percentile

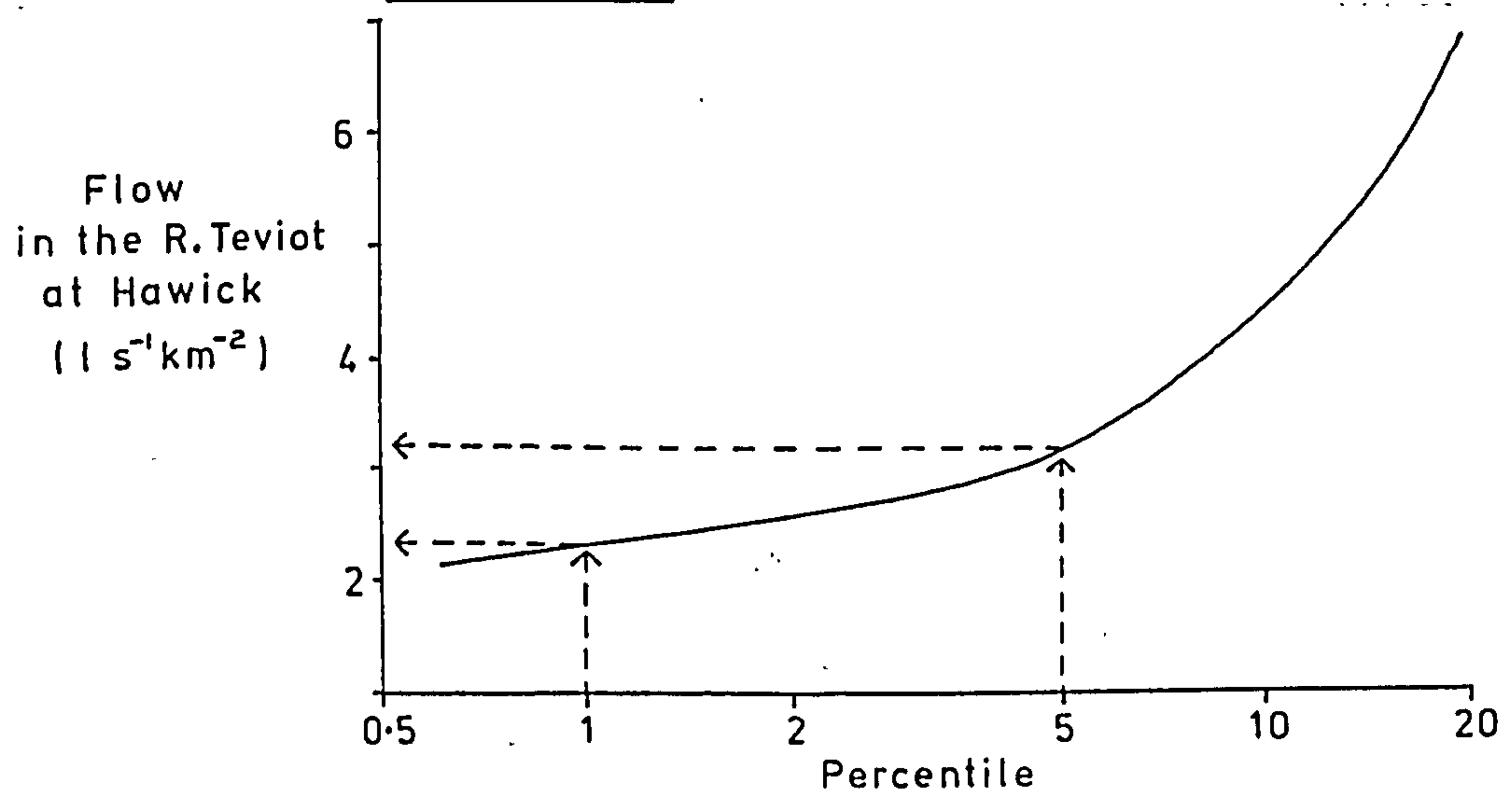
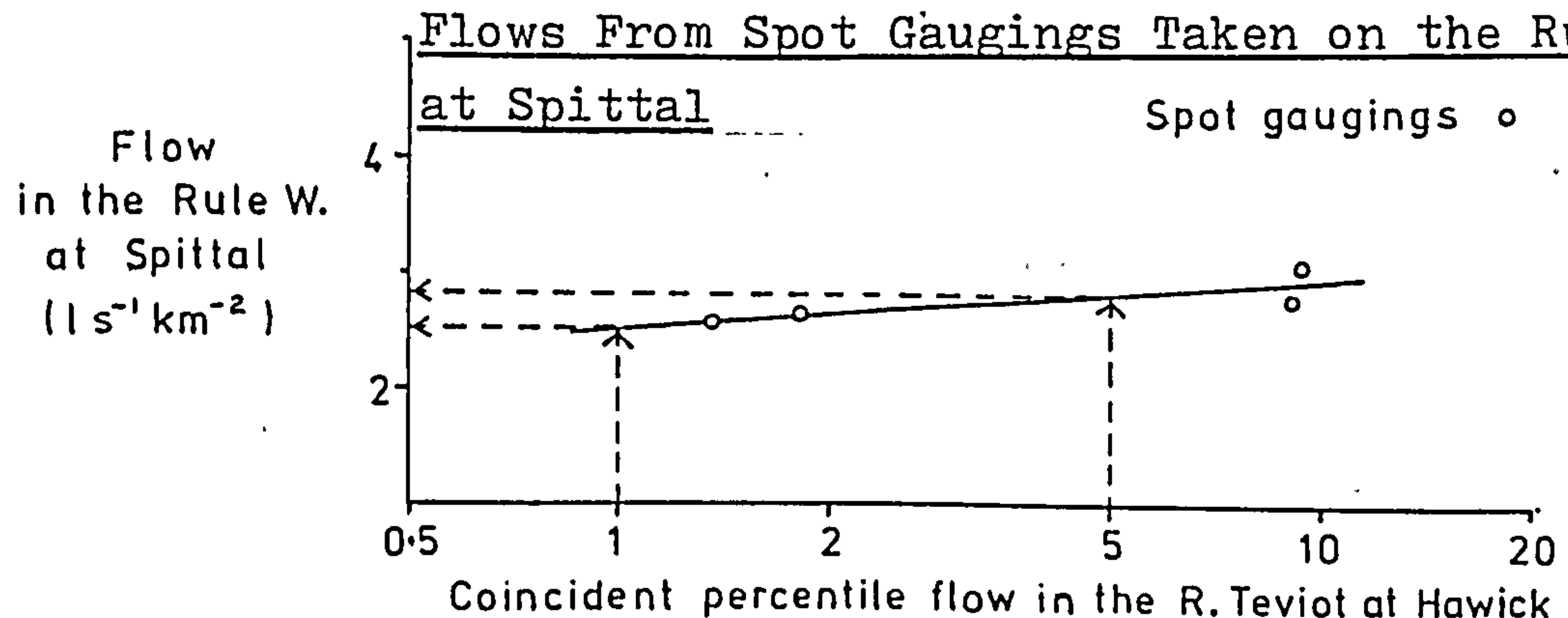


FIGURE 2.16.3 : Use of the R. Teviot at Hawick as the Index Station to Estimate Long Term 1 and 5 Percentile Flows From Spot Gaugings Taken on the Rule W. at Spittal



Hunt stresses the need for spot gaugings to be made when flow consists largely of ground water effluent, however, it would seem reasonable to assume that this is indeed the case when dealing with such low flows.

The presentation of all spot gaugings, their conversion to percentile flows, and the subsequent estimates made for the long term 1 and 5 percentile levels in this thesis is prohibited by the vast amount of data involved. In fact, estimated long term (1961-78) 1 and 5 percentile flows were derived for some 350 individual catchment areas. However, by way of an illustrative example of the technique employed, a series of four spot gaugings, taken by the Tweed River Purification Board during periods of low flow between 1971 and 1974 on the Rule Water at Spittal (catchment area  $93.5 \text{ km}^2$ ), is shown on Fig. 2.16.3. This location is situated 10 km east of the index station on the R. Teviot at Hawick. By assigning each spot gauging with the percentile flow value occurring on the same day at the index station, an estimated partial Flow Duration Curve can be derived, as in Fig. 2.16.3. The estimated long term 1 and 5 percentile flows of 2.5 and 2.8  $\text{l s}^{-1} \text{ km}^{-2}$  respectively can then be read off.

Measured and derived flow levels such as those above often required further processing, since the aim of this exercise is to map natural flows. Therefore, the influences of hydro-electric schemes, artificial discharges and water supply reservoirs and abstractions were taken into account where details of, for instance, reservoir compensation flow

and dry weather sewage effluent discharge were available. If not, the affected catchments were omitted from the analysis. The distribution and size of catchments for which 1 and 5 percentile flows were processed are entirely dependent on the availability and acceptability of flow data.

Since the great majority of 1 and 5 percentile flows obtained were of a "nested" nature, those flows associated with catchment areas between two or more gauging sites were derived on the basis of proportional areas. Indeed, the 1 and 5 percentile flow values for each residual catchment are shown in units of  $1 \text{ s}^{-1} \text{ km}^{-2}$  in Appendix 5. Here, the values of areal yields for both flow levels are shown for each of five Purification Board Areas.

#### 2.5.1.3 Usefulness of the Derived Percentile Flows

The previously mentioned "nested" nature of the percentile flow estimates renders any assessment of the accuracy of residual measurements difficult, since they are derived from various combinations of the three categories of flow measurements. Some indication of the errors likely to be associated with each of the three is now given.

Errors arising from flows gauged at long term sites, which can be assumed to be minimal, will be present in all percentile flow estimates since their derivation is at least partly dependent on them.

As regards additional errors associated with the 1 and 5 percentile flow estimation from the second category



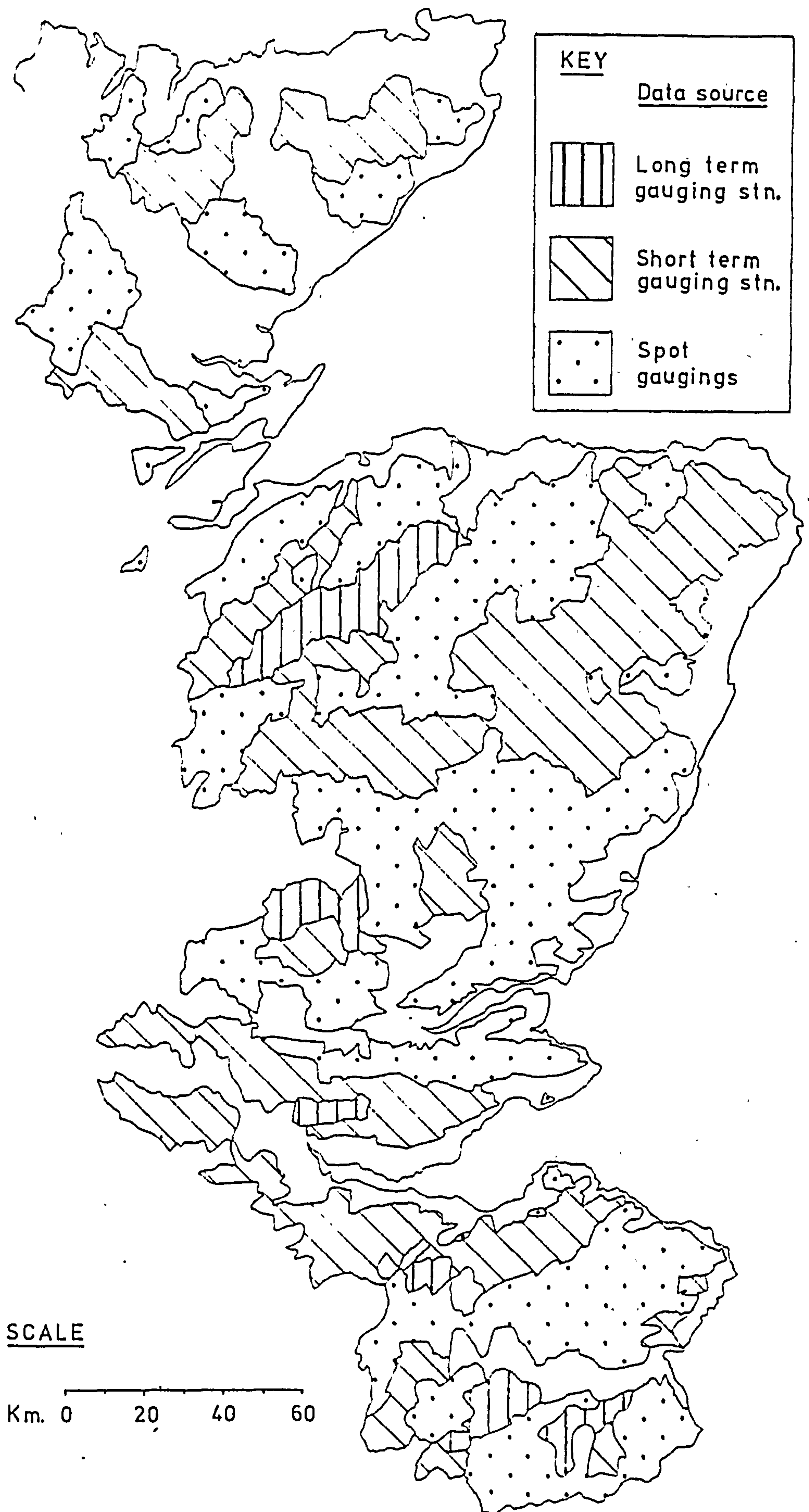
of measurements, Searcy (1959) encountered underestimates of about 15% of the 5 percentile flow when extending a 5-year record to a 25-year long term period. One would expect this error margin to decrease with proportionately smaller differences between record lengths.

In the case of the "spot gaugings", two major sources of error are apparent; that involved in the gauging itself; and that subsequently associated with percentile flow derivation. In the first case, detailed work by Anderson (1961) assessed the errors involved with current meter gaugings. For example, using 10 meter locations for the 0.2 and 0.8 depth method with a 45 second time period of observation (a largely standard procedure), he calculated that discharge errors would be less than 5% for 67% of cases. However, for low flows in small catchments, where the possible number of meter locations would be much less than 10, errors of greater magnitude could be expected.

Furthermore, the procedure used to estimate long term percentile flows from spot gaugings involves an additional source of error. Using the method adopted in this study, Hunt (1963) underestimated 1 and 5 percentile flows by up to 10%.

The predominant one of the three categories of flow measurement (determined on an areal basis) used in the derivation of residual 1 and 5 percentile flows is indicated on Fig. 2.17. Although this is by no means a perfect representation of the relative accuracy of derived

**FIGURE 2.17 : The Predominant Type of Flow Data Used in the Derivation of Nested Long Term 1 and 5 Percentile Run-Off Yields in the East of Scotland**





percentile flows, it does reveal the large dependence of this study on spot gaugings in certain regions, notably in the Tweed and Tay River Purification Board Areas.

The further consideration of residual catchment size (see Appendix 5) must also be taken into account as regards the usefulness of individual percentile flow estimates. A better definition of geographical variation would be obtained using many values for small catchments, rather than a reduced number of integrated flows from larger catchments. Thus, although percentile flows referring solely to gauging station sites may be the most accurate, they are not necessarily the most useful in delineating the areal distribution of low flow values, because they tend to come from relatively large catchment areas.

#### 2.5.1.4 Construction of 1 and 5 Percentile Run-Off Maps

Using the 350 areal estimates for both 1 and 5 percentile flows, (as shown in Appendix 5), it was decided that the best means of representing them on a national scale would be to construct isometric maps. This was because of; (i) the large number of sample catchments which provided a well-defined distribution of low flows; and (ii) the possible misrepresentation involved in the alternative method of identifying catchments within different classes of flow. This is likely, because catchment boundaries will not necessarily coincide with lines separating areas of different low flow characteristics. This is



particularly relevant in the case of the larger sample catchments where one integrated flow value may conceal the range of 1 or 5 percentile yields within the catchment.

The main difficulty associated with the derivation of an isometric illustration is that the values to be used are not point values, but measurements referring to areas, all of various shapes and sizes. The procedure adopted to overcome this difficulty was as follows. Firstly, the centroid of each area was allocated the integrated flow value for the catchment as a whole. These estimated point values were used to draw preliminary isometric lines, positioned by proportional distances between points. Then, taking into account both the area and shape of each sample area, the isometric lines were redrawn so as to correspond with the surrounding spatial distribution of areal flow values. Thus, the areally proportionate sum of yields derived from the isometric lines in a given catchment, could be summed to give the original integrated value for the whole sample catchment. As far as possible, all estimates represent natural flow. However, the effects of natural storage in the form of ponds or lochs could introduce some unexplained variation.

The resulting maps of 1 and 5 percentile flow for the eastern half of Scotland are shown in Figs. F.1 and F.2 respectively, which are located in the sleeve on the back cover of this thesis. Isometric lines are placed at intervals of one  $1 \text{ s}^{-1} \text{ km}^{-2}$ , and additional lines representing  $0.5 \text{ s}^{-1} \text{ km}^{-2}$  have been included where necessary.

Where isometric lines are dotted, this depicts situations where there was considered to be insufficient data available to draw a reliably accurate solid line.

#### 2.5.2 Explanations for the Geographical Variation of Low Flow Yields

In both Figs. F.1 and F.2, a large range of variation for similar percentile flows is apparent. For example, in the R. Tweed basin, 5 percentile flows range from a maximum of  $8 \text{ l s}^{-1} \text{ km}^{-2}$  to values less than 0.5, some being of the order of  $0.1 \text{ l s}^{-1} \text{ km}^{-2}$ .

The most predominant influence in the patterns revealed in the above figures is that of rainfall, probably not only in terms of its quantity, but also its temporal distribution. The effect of the latter variable would be difficult to illustrate, but not that of the former. Areas of higher rainfall tend to have higher 1 and 5 percentile run-off values. For the example quoted above, the average annual rainfall in the upper Tweed basin is around 2000mm, whereas it is only around 700mm in the area of lowest run-off.

The other climatic influence on run-off is that of potential evaporation, whose geographical variation cannot be accurately estimated. However, it would appear that this variation is of negligible proportions in comparison with that of rainfall (Ministry of Agriculture, Food and Fisheries, 1967).



Earlier reference to the Institute of Hydrology's (1978) study has indicated the second major influence on low flow levels as that of geology. Both the water retention and release characteristics of rocks can be expected to affect 1 and 5 percentile yields. The solid geology of east Scotland is extremely varied in type, but not, according to the above study, in terms of its water storage characteristics. All the major geological formations, ie; the igneous and metamorphic rocks of the north-east; the Old Red Sandstone of eastern Tayside; the carboniferous rock in the area around the Firth of Forth; and the Silurian and Ordovician formations in the Borders Region; are grouped together under the classification of "low storage" characteristics. Therefore, it is the effects of superficial deposits which one would expect to be more pronounced and identifiable.

The drift geology of eastern Scotland is such that high ground tends to be either "drift free", or covered with either hill peat or boulder clay. This latter deposit is by far the most common on low ground, but small areas of gravel deposition (both glacial and water-borne) are apparent in river valleys and coastal stretches. The effects of the type and extent of different superficial deposits can be shown not only with reference to estimated 1 and 5 percentile run-off levels, but also the relationship between these levels, which gives an indication of underground storage and streamflow recession behaviour.



The following examples make use of comparisons between areas of similar solid geology and average annual rainfall to isolate the effects of superficial deposits on 1 and 5 percentile yields. On higher ground, such deposits are either of hill peat or boulder clay, or are completely absent. The effects of the last two situations can be compared with reference to two areas at the top of the R. Tweed basin where the average annual rainfall is 1200-1600mm. In the headwaters of the R. Tweed itself, where there is no drift, the 1 percentile run-off is 3 to 4  $\text{l s}^{-1} \text{ km}^{-2}$ . Thirty kilometres to the south-east, in the boulder clay around the headwater of the R. Teviot, this yield is only around 2  $\text{l s}^{-1} \text{ km}^{-2}$ . On higher ground, low flow yields tend to be consistently greatest in areas with no drift, and the largest 1 and 5 percentile flows in eastern Scotland are to be found in the drift-free parts around the headwaters of the R. Avon in the Grampians, where the average annual rainfall is 1600-2000mm. This area, where 1 and 5 percentile flows are as high as 7 and 9  $\text{l s}^{-1} \text{ km}^{-2}$  respectively, is easily identified on Figs. F.1 and F.2 respectively. In an area of similar annual rainfall, but with an extensive covering of hill peat only 40 km to the east, the low flow yields are only half of the above values. The possible extreme effects of peat deposits in severely reducing 1 and 5 percentile run-offs are shown in Caithness, in the far north. Here, both of these yields are around 1  $\text{l s}^{-1} \text{ km}^{-2}$  or less, over a large land area covered in hill peat.

At the lower altitudes, and correspondingly drier climates, there are no significant drift-free areas in eastern Scotland. The limited extents of the largely isolated areas with gravel deposits render a comparison with widespread boulder clay drifts rather difficult. There are however, notable areas of glacial gravels overlying the Old Red Sandstone of the Dean W. catchment in Tayside and the R. Eden catchment in Fife (Nos. 4 and 13 respectively in Fig. 2.10). In these specific areas, the 5 percentile run-off, at around  $3 \text{ l s}^{-1} \text{ km}^{-2}$  is double that of the surrounding parts covered in boulder clay. Also significant is the similarity between this and the 1 percentile yield, notably in the R. Eden catchment, where it is  $2.5 \text{ l s}^{-1} \text{ km}^{-2}$ . This effect of low flow maintenance can be linked to the water storage properties of the gravel deposits.

However, it is not only the type, but also the depth of superficial deposits which can have a marked influence on low flow yields. For example, in the north-east of the Grampian Region, where the average annual rainfall is 800-900mm, and the predominant drift cover is boulder clay, the 1 and 5 percentile yields are typically 3 and  $4 \text{ l s}^{-1} \text{ km}^{-2}$  respectively. Such values are around twice as great as those apparent in similar areas in the east, notably those inland from the Firths of Tay and Forth. This large difference can be explained by the great depth of the drift in the Grampian Region, which Woodward (1907) reports as being 100 feet (30m) deep in places. Such a



depth would greatly increase the quantity of water available for release to watercourses in dry conditions.

One further group of possible influences on 1 and 5 percentile yields are those concerned with land use, and particularly with different types of ground cover and artificial drainage systems. Some of the as yet, unexplained small-scale variation in Figs. F.1 and F.2 could perhaps be explained with reference to these features. However, Newson (1978) found that water yields from forested and grassland areas in Wales did not differ significantly during the 1976 drought. This led him to conclude that land-use effects were subordinate to those of rainfall variability, soil and geology, in relation to the maintenance of river flows during dry periods. This would also appear to be the general case in the east of Scotland.

### 2.5.3 Use of 1 and 5 Percentile Run-Off Maps

Since Figs. F.1 and F.2, depicting 1 and 5 percentile run-off yields respectively, provide a near complete coverage of eastern Scotland, an assessment of low run-off values experienced during the 1971 to 76 period can be made for the whole area, rather than just sample catchments. For example, with reference to Fig. 2.14, and using station No. 2 (the R. Deveron at Avochie) as a reference, it can be estimated that for the 16% of the time in 1976 that flows were less than the 1 percentile level, the coastal areas in Banff were yielding less than  $1 \text{ l s}^{-1} \text{ km}^{-2}$ .



Also, use of station No. 7 (the R. Tyne at East Linton) as a reference would suggest that yields were less than  $0.5 \text{ l s}^{-1} \text{ km}^{-2}$  (the 5 percentile level) in coastal parts of East Lothian for 33% of the time in 1973. In that year, the run-off from a typical coastal catchment of say,  $10 \text{ km}^2$  would have been less than  $5 \text{ l s}^{-1}$  for 120 days.

In a more general context, the information displayed on Figs. F.1 and F.2 could be very useful in the field of water resource management. The complexity and degree of geographical variation of 1 and 5 percentile yields (similar to that found by Clarke and Newson (1978) for minimum instantaneous discharges in Wales during the drought of 1976) requires that specific note be taken of local low flow characteristics for water management purposes. Although the vast majority of the land area of eastern Scotland has 5 percentile yields greater than  $1 \text{ l s}^{-1} \text{ km}^{-2}$  and 1 percentile yields of more than  $0.5 \text{ l s}^{-1} \text{ km}^{-2}$ , in some areas of low rainfall and unfavourable geology, low flow yields smaller than these values are common. The parts of the country concerned are; Caithness in the far north; the area surrounding the Firth of Forth, notably East Lothian; and the lower part of the R. Tweed basin in the Borders. In such areas in particular, it is important that water management policies take account of the probability and the magnitude of the exceptionally low run-off yields which can occur. For instance, in Caithness, water supplies are designed on a minimum run-off of around  $0.1 \text{ l s}^{-1} \text{ km}^{-2}$  (Highland Regional Council, 1978),

whereas prior to the drought of 1955, the design value was twenty times greater. The extreme nature of low flows in drought conditions, such as those of 1955, would not always be accurately recorded, and it could be expected that the events of the 1971-76 period might have caused particular problems for water managers in small catchments confined to any of the above areas. The relevant drought impacts are discussed in Section 3, but prior to that, the following pages are concerned with a subject of equal importance for water resource managers in relation to the 1971-76 drought, ie. its recurrence probability.

## 2.6 THE HYDROLOGICAL EVENTS OF 1971-76 PUT INTO HISTORICAL PERSPECTIVE

### 2.6.1 Introduction

The extreme nature of the climatic and especially the hydrological events during the 1970's, such as the widespread occurrence of three-year rainfall totals less than 80% of average, and annual run-offs as low as 10% of average (which represented only 11mm in East Lothian in 1973), requires that some investigation of the likelihood of their repetition is made. The limitations of the rainfall recurrence probabilities, corresponding to



return periods of up to one thousand years, estimated from Meteorological Office data, have been indicated in Section 2.3.1.3, along with the need for records of long duration. Such long records would allow the events of the 1971-76 period to be put into historical perspective, not only by use of recurrence probabilities, but also by some consideration of the rather topical matter of climatic change. Concern has been raised for instance, by Hay (1974) and Lamb (1966), who note that the incidence of westerly winds over Britain increased from 1861 A.D. to a peak in the 1920's, and that a notable decline in their frequency has occurred since the 1950's. Such a decrease in the prevalence of westerlies can be associated with a reduction in rainfall over the country. Such recent changes in climate are, Wright (1975) argues, "probably merely short term fluctuations, as is seen when longer periods of data can be examined". The importance of such fluctuations, over periods of about 1 to 50 years, in relation to human activities is emphasised by Wright when he states that their nature is much more severe and abrupt, than those of say, transitions between glacial periods. These involve relatively subtle changes in rainfall and run-off over much longer time spans.

Short term changes in the climate of south-east Scotland are considered by Thom and Ledger (1976). Using the two hundred year old rainfall record for Blackford Hill, Edinburgh, they derive a measure of "excess winter rain", which can be related to annual run-off values. In



this way, 1972 is identified as the driest year over the whole period of record. It is notable however, that no directly measured run-off record has, to the author's knowledge been used to consider the nature of the variation and fluctuation in a given climate. The obvious reason for this is that no sufficiently long record has hitherto been available. However, the derivation and analysis of such a record, of almost one hundred years duration, is now presented for a reservoired catchment for which a wealth of hydrological data was found to exist.

#### 2.6.2 Derivation of a Long Series of Annual Run-Off

Gladhouse Reservoir and its 24.7 km<sup>2</sup> catchment area are located in the Moorfoot Hills in Midlothian, 20 km south of Edinburgh. This source of water supply, capable of storing up to 8133 Ml was developed by the Edinburgh and District Water Trust under the Edinburgh and District Waterworks Act of 1874, and became operational around ten years later. At this time it supplied over half of Edinburgh and Midlothian's water requirements, however its proportionate contribution to the area's total consumption has gradually decreased to around 15-20% in the 1970's.

Comprehensive records of reservoir levels, compensation water outflows, and overspill levels have been kept, on a daily basis, since 1885, along with weekly summaries of quantities of water delivered to the public supply. All of this information has kindly been made available by Lothian Region Water Supply Services.

The accuracy of the measurements involved is unknown, especially those recorded by meters in supply pipelines. However, some indication of the reliability of the daily recordings can be gauged from their precision. The reservoir level was measured to the nearest half-inch, which can represent a volume of up to 20ml. Since it represents less than one day's typical consumption, this source of error is negligible over a period of several months. Spot readings of daily outflow depths over two weirs of 6 feet and 150 feet in width are recorded to the nearest  $1/8$  or  $1/4$  inch, depending on the observer. When expressed as a quantity of flow, this level of precision in itself represents very small amounts, especially at low depths of overflow. However, large errors could be introduced by consideration of the unrecorded variation in overflow level in any one day. Thus, in those years where a large quantity of overflow occurs, there will be an increased risk of error in the estimation of the total quantities of water involved.

One further source of loss from the reservoir, ie. evaporation from its surface, required investigation. This was done by using a simple two-season model based on winter and summer average potential evaporation rates (Ministry of Agriculture Food and Fisheries, 1967) in conjunction with mean surface areas available in each season. The inclusion of this approximately estimated variable can be justified by consideration of the fact that it can



account for up to 5% of the total annual inflow.

Simple computations involving all the above measurements concerning reservoir levels and losses from the system, can be used to derive inflow quantities over given time periods. The number of sources, and the possible extent of the errors involved would indicate that the data available are more suited to providing an annual rather than monthly run-off series. The choice concerning the most suitable 12 month period is a more difficult matter. However, the standard water-year period from October to September was chosen since; (i) the archived records were most suited to analysis based on this time period; and (ii) errors attributable to the least accurately measured component, ie. overspill, could be confined to given 12 month periods. This is because each seasonal period of overspill was contained in the appropriate water-year.

There is the disadvantage however, that since periods of soil moisture deficit could straddle consecutive 12 month periods, then direct comparisons between annual rainfall and run-off could be misleading.

### 2.6.3 Reliability of the Derived Run-Off Record

Obvious and outstanding errors occurring in any of the 92 annual values could be identified by comparing the derived run-off series with coincident rainfall data. Indeed, a rainfall record has been kept at the reservoir site over



the same period. Using Meteorological Office estimates of average areal rainfall, the annual water-year precipitation values were multiplied by a factor of 1.198 to provide estimates of catchment rainfall.

Fig. 2.18 provides a means of making such a comparison of annual run-off and estimated catchment rainfall. The differences between annual rainfall and run-off all fall in the range 250-550mm. Considering further variables such as annual evaporation, and moisture deficits and surpluses carried between water years, then there would appear to be an acceptably consistent relation between annual run-off and rainfall for the  $24.7 \text{ km}^2$  catchment area. In addition, the run-off values would appear to be of the correct magnitude in relation to those of rainfall.

A more thorough assessment of the reliability of the run-off series can be made by comparing it with a directly-gauged record of run-off. Fig. 2.19 shows the relationship between the derived run-off series, and that for the 13 years of measurements of gross mean annual flow at Prestonholm gauging station (catchment area  $112 \text{ km}^2$ ) situated further downstream on the same river, the South Esk. As expected, the annual run-off values for the furthest upstream  $24.7 \text{ km}^2$ , which is the area of highest rainfall over the larger catchment, are typically 100-150mm greater than those for the whole area. Also, the correlation coefficient of 0.95 compares favourably to that of 0.92 obtained for the Prestonholm data measured against the annual run-off for the adjacent catchment ( $82 \text{ km}^2$ ) measured

**FIGURE 2.18 : Annual Water - Year Rainfall and Run-Off for  
the Gladhouse Reservoir Catchment for the  
Period 1885/86 - 1976/77**

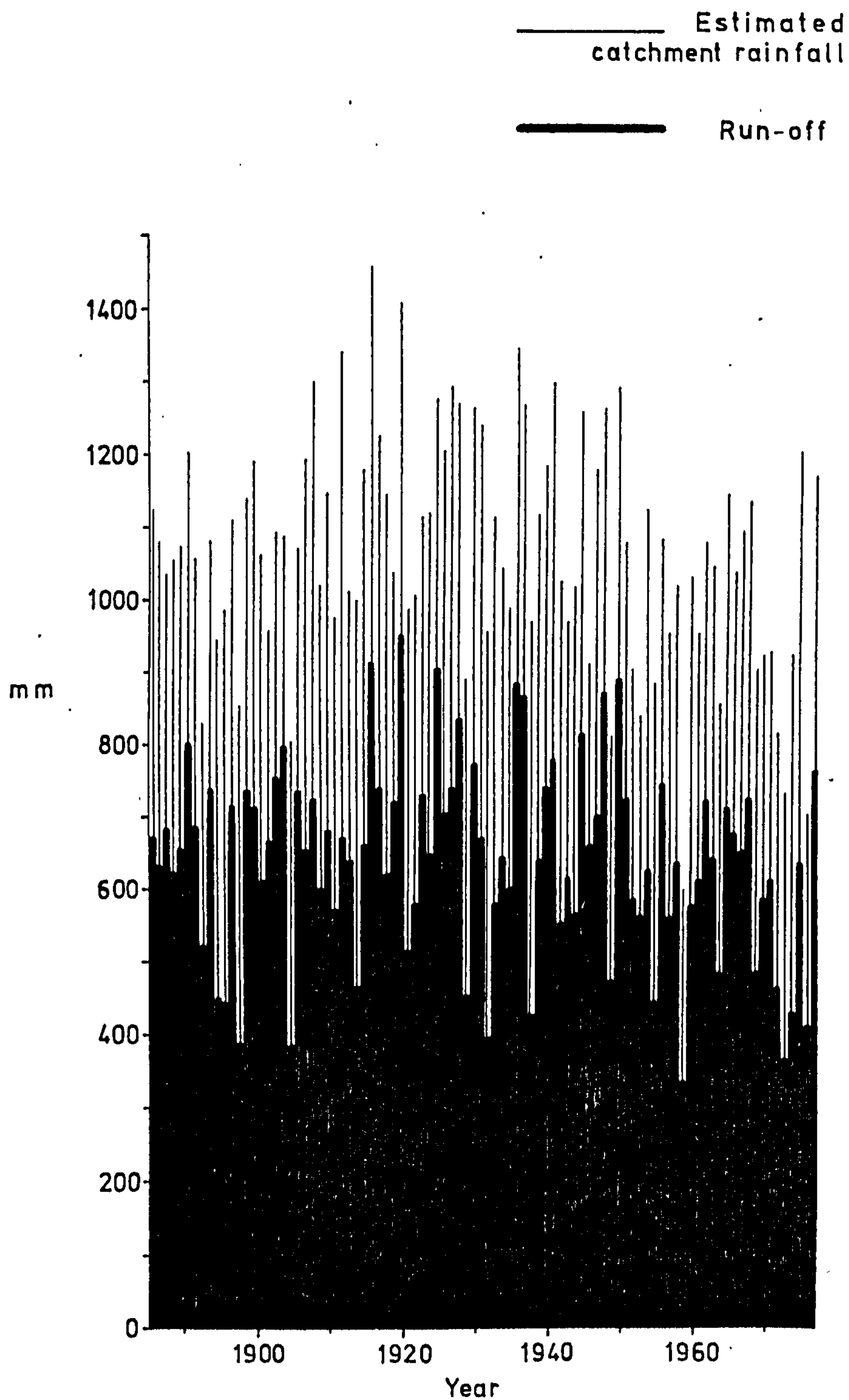
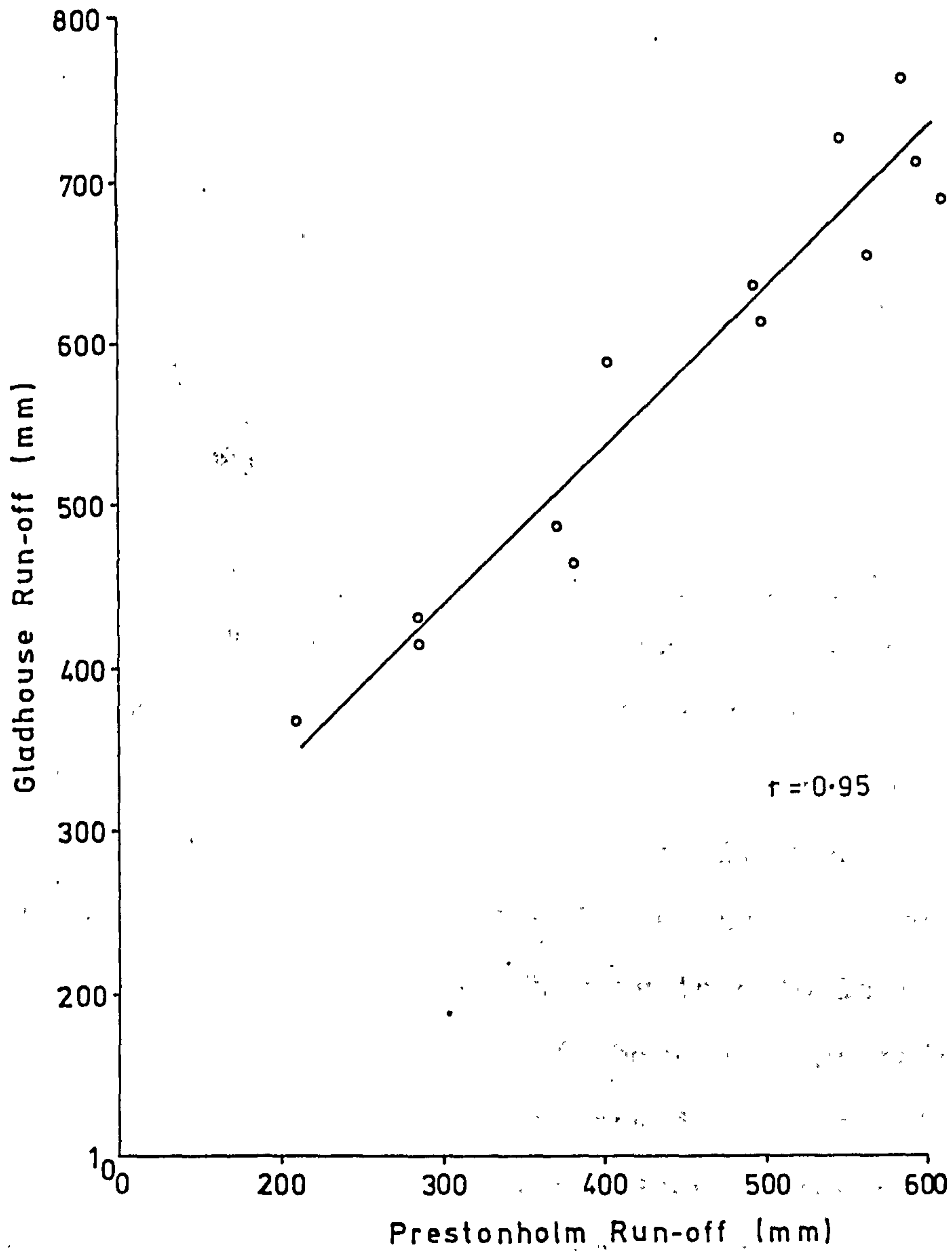


FIGURE 2.19 : Correlation of Annual Water - Year Run-Off (1964/65 - 1976/77) for the Catchments of Gladhouse Reservoir and of the R. South Esk at Prestonholm





at Dalmore Weir on the R. North Esk.

All the above evidence would tend to verify that, for at least the latter 13 years of the derived run-off series, the measurements are of a consistent and reasonably accurate nature. Furthermore, since no land use changes, which could significantly affect run-off occurred over the 92-year period of record, and the same methods of measurement of storage level and outflows have been employed over the period, then it would appear to be safe to extend this assessment of reliability and accuracy over the entire 92-year series of run-off values.

#### 2.6.4 The History of Climatic Fluctuation at Gladhouse

Fig. 2.18, depicting the annual water-year series of catchment run-off and rainfall at Gladhouse Reservoir, illustrates the previously mentioned recent variations in Britain's climate. The trend involves an increase in rainfall and run-off from the latter part of the 19th century up to the 1920's. This is then followed by a relatively sustained period of above average rainfall and run-off, and then a decreasing trend from the 1950's to the late 1970's. This latter 30-year period included several drought events which affected Scotland, ie. those of 1955, 1959, and the most recent one over the period 1971-76. This 6-year drought event is by far the longest and severest in south-east Scotland since at least 1885.

One has to go back considerably further than 1885 to find an event of similar magnitude and duration as that of the 1970's. The two hundred year rainfall record for Blackford Hill, Edinburgh (in Appendix 6) would suggest that the dry period most comparable with that recently experienced occurred some 170 years previously. In fact, prior to 1885, this record indicates a rather wet period similar to that of 1920-50, beginning in the 1850's, which followed a 40-year period of variable, but "trendless" rainfall. Prior to this, during the first decade of the 19th century, a sustained period of dry years similar to those of the 1970's is found. Indeed, for periods of 2-4 years, the more recent event was more severe, but it involved smaller rainfall deviations over periods of 5 or more years, and 1 year.

This comparison confirms the extreme abnormality of the events of the 1971-76 period, at least in terms of rainfall, in south-east Scotland. It also indicates that even such a rare climatic fluctuation falls, at least partially, within the realms of the past, and expected future variation in climate. It would be most useful to attempt to reliably assess the recurrence probabilities of the events of the 1970's, both in terms of rainfall and run-off, particularly for those of a duration of two to four years, which are unprecedented for at least two hundred years in south-east Scotland.



## 2.6.5 Recurrence Probability Analysis

### 2.6.5.1 Methodology

To ensure a sound basis for an analysis of recurrence probabilities, the nature of climatic variation over the 92-year period must be assessed in relation to its representativeness of the whole range of possible variation. The facts that it includes periods at both extremes; ie. the period 1920 to 50, and the 1970's; and that events of similar duration and magnitude appear once again in the 200-year Blackford Hill rainfall series, would seem to indicate the suitability of this period for a more detailed analysis of recurrence probabilities.

The skew nature of the annual rainfall, and particularly the run-off, distribution was most suited to curves of the Pearson III i type, and those shown in Fig. 2.20 were fitted using the techniques of Pearson (1895) and Kelley (1924). The accompanying histograms representing the actual distributions of annual rainfall and run-off show that a satisfactory fit is obtained using these curves. In each case the horizontal scales are in units representing proportions of the median, to facilitate the comparison of the variability of rainfall and run-off relative to "normal" values. A series of such curves was also calculated for both rainfall and run-off for series of overlapping durations of 2 to 6 years.

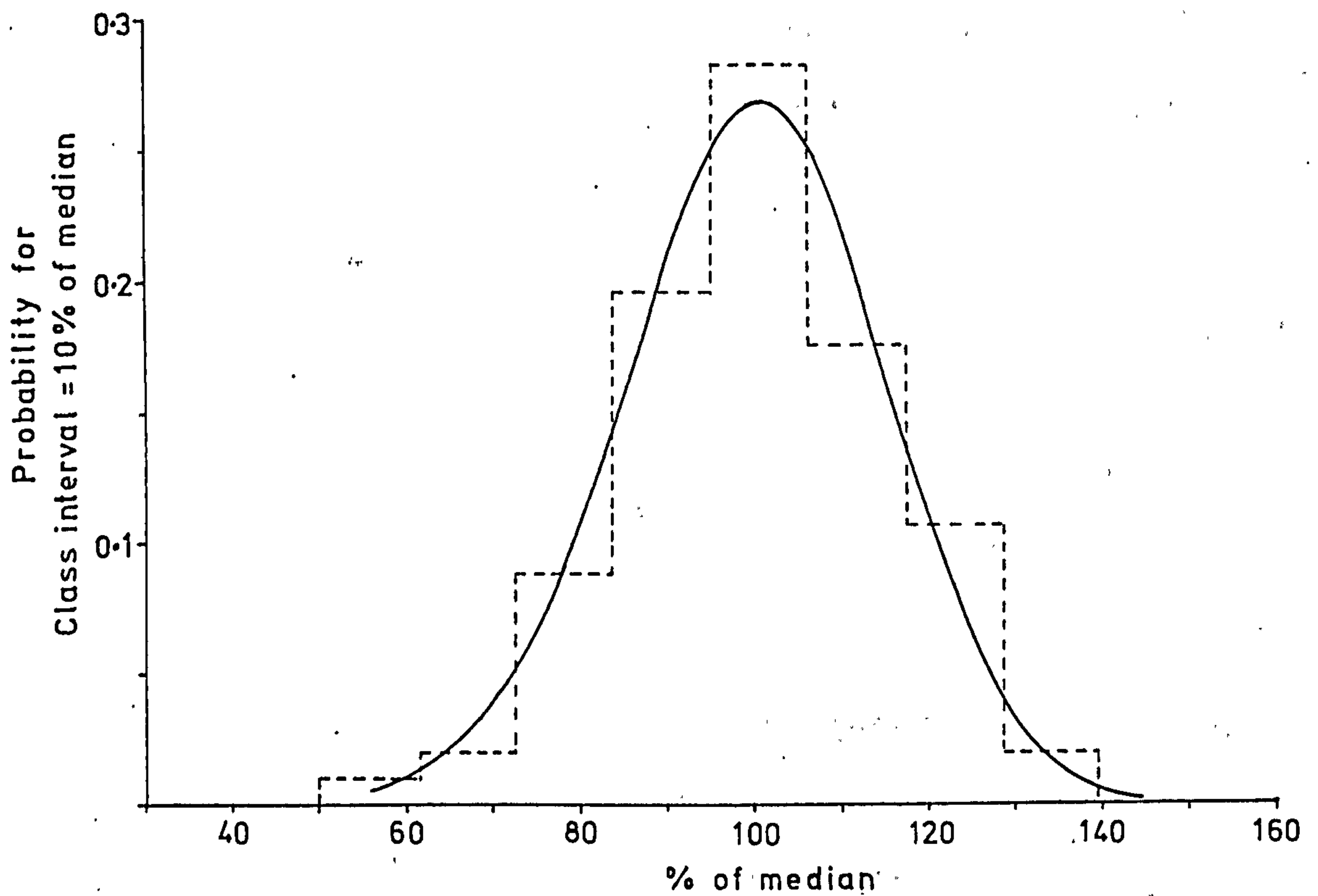
The probability of occurrence of a given annual event is given by the appropriate area under the relevant



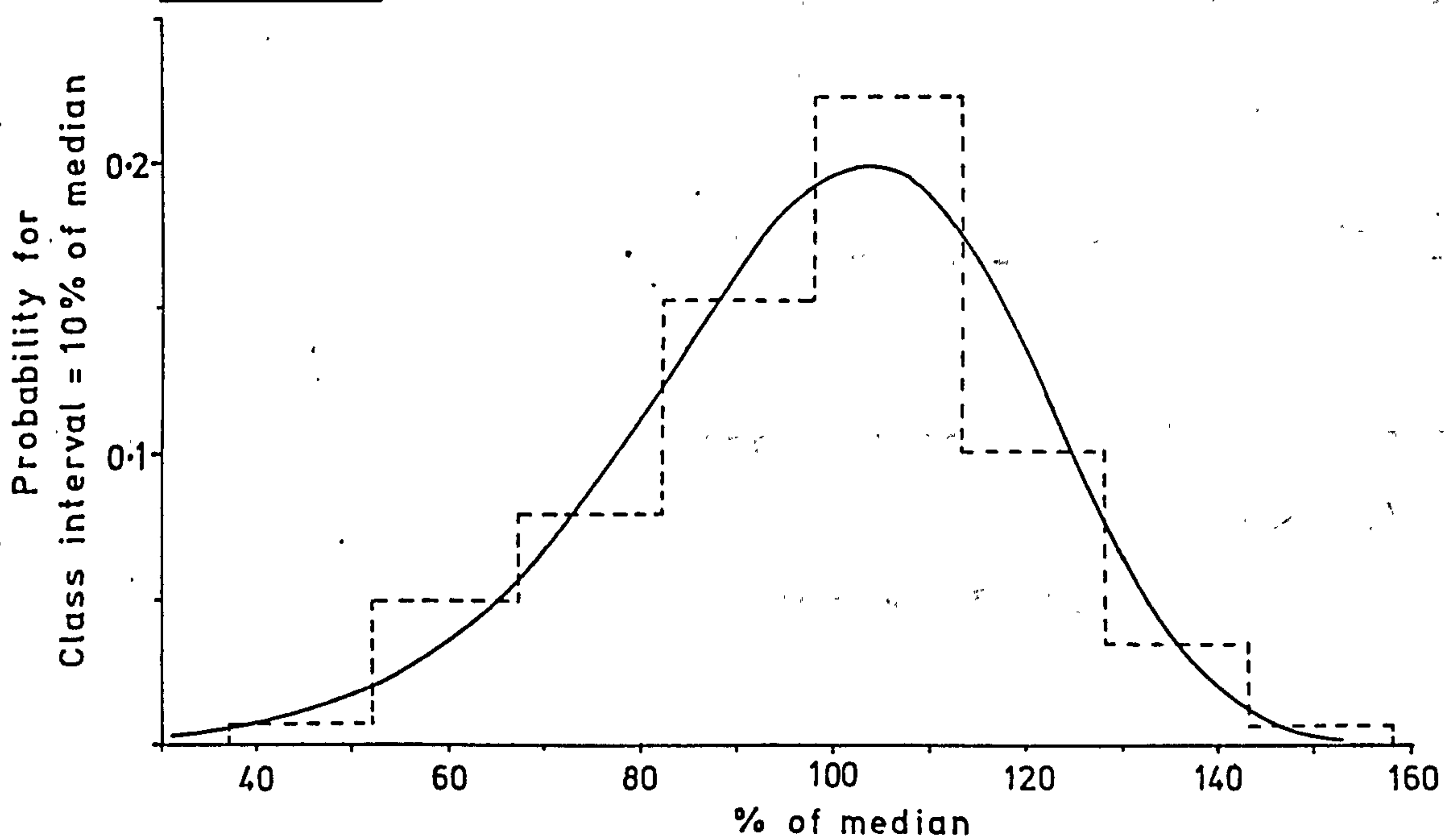
FIGURE 2.20 : Actual and Derived Probability Distributions  
for Gladhouse Reservoir Catchment Water - Year  
Events of:

----- actual  
 ————— derived

(1) Rainfall



(2) Run-off



curve, readily calculated by integration. For overlapping multi-year periods, the estimation of such probabilities is complicated by serial correlation. However, Waldo-Lewis and McIntosh (1952) presented a method of taking this factor into consideration. In this technique, an adjusted probability is given by the formula,

$$\text{Pr (adj)} = \text{Pr (initial)} \times \frac{R_i}{D} \quad \dots\dots 3$$

where  $R_i$  = No. of repeats

$D$  = duration of time unit in years

The No. of repeats,  $R_i$ , can be calculated in two parts, corresponding to an equivalent independent value, and an additional one dependent on the degree of serial correlation. The first part can be shown in all cases to equal the value of  $D$ , after Senedecor and Cochran (1973). The second element  $R_i$  (2) is given by,

$$R_i (2) = 1 + \frac{2}{N} ((N-1) r_1 + (N-2) r_2 + \dots + (N-i) r_i + \dots + 1 \times r_{n-1}) \dots 4$$

where  $N$  = the No. of overlapping totals ie., in this case

$$92 - (D-1)$$

$r_i$  =  $i^{\text{th}}$  serial correlation coefficient.

The values obtained for  $r_i$ , up to  $i = 6$  are shown for both annual series of rainfall and run-off in Appendix 7. Notably, the third degree serial correlation coefficient is the greatest in each case, and overall, the values for annual run-off are markedly lower than those for rainfall, to the extent that some are even negative. Consequently, the adjustment factors for recurrence probability ( $\frac{R_i}{D}$ ) are considerably higher for multi-annual rainfall values than those for run-off, as is shown in Appendix 7.

Using the assigned probability curves, and the adjustment for serial correlation necessary for overlapping periods of 2 or more years, it is possible to construct cumulative probability curves, such as those shown in Figs. 2.21 (1) and (2). These relate to the annual series of rainfall and run-off, the former illustrating recurrence probabilities of events expressed in terms of their absolute deviation (mm), and the latter proportional deviations, both from median values.

Although annual run-off values are less variable than those of catchment rainfall in absolute terms, in relative terms the former shows a much greater range of variation, particularly at the low end, as Fig. 2.21 reveals. For example, a water-year event involving a recurrence probability of 0.01 (ie. a return period of 100 years) requires 64% of median rainfall, but only 45% of median run-off.

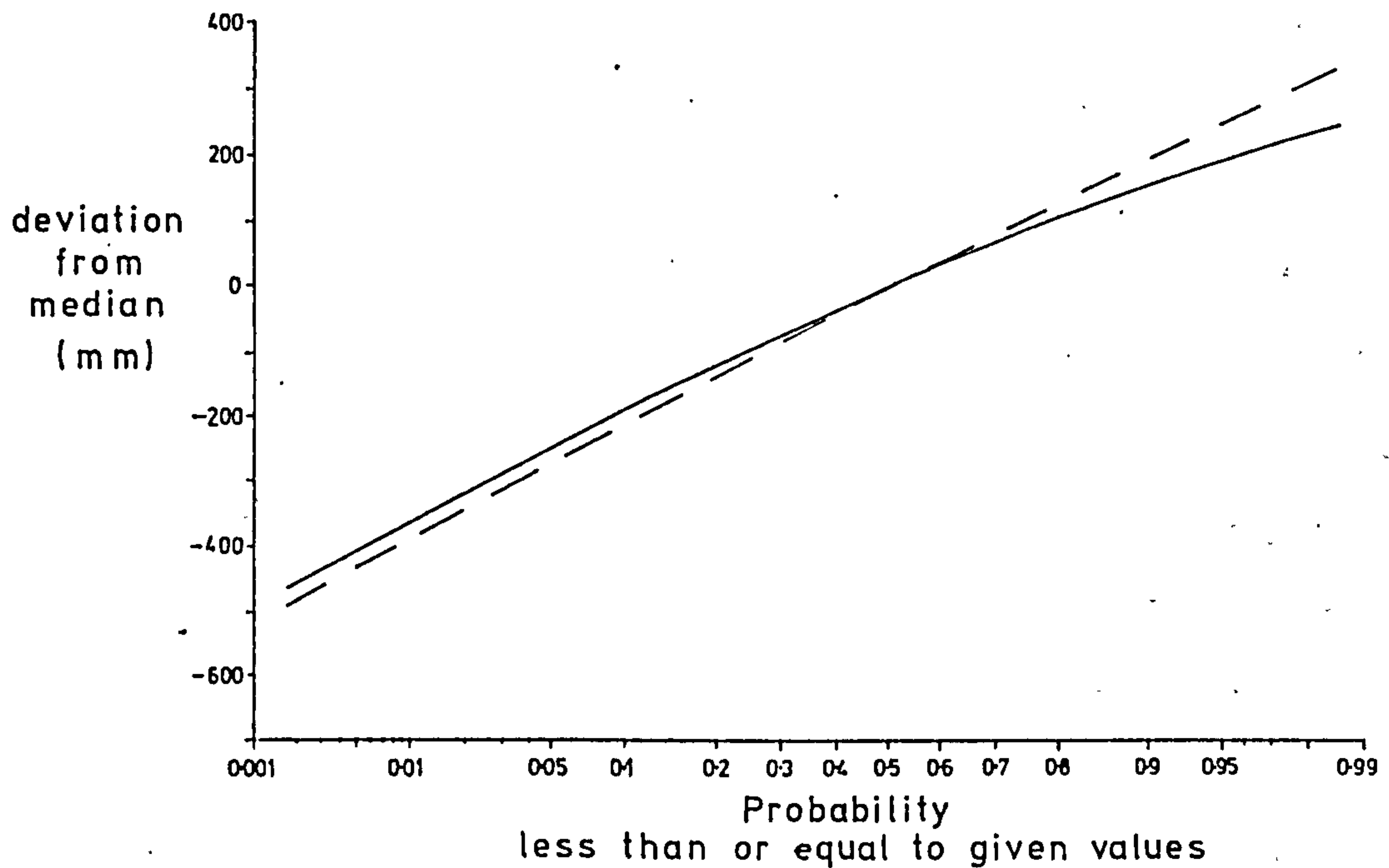
This difference between rainfall and run-off variation decreases significantly when longer durations are concerned. For instance, a return period of 100 years corresponds to



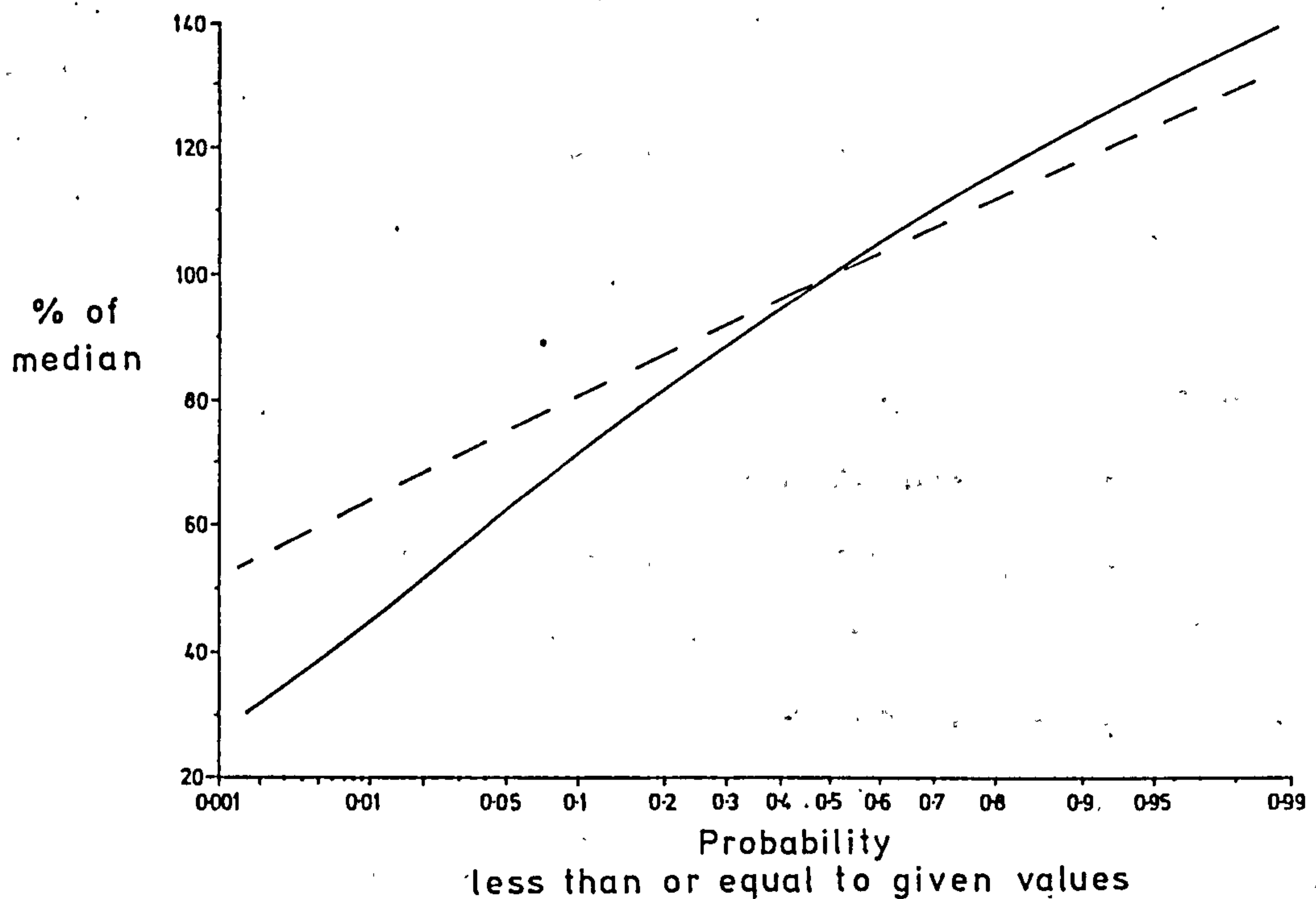
**FIGURE 2.21 : Annual Recurrence Probabilities of Variations in Water - Year Rainfall and Run-Off Events for the Gladhouse Reservoir Catchment for:**

— — — Rainfall  
 ————— Run-off

(1) Absolute deviations



(2) Deviations relative to median values



74% of median rainfall and 62% median run-off over a 2-year period. Over a 6-year period, these values become 78 and 74% respectively.

A note as to the concurrence, or lack of it, as regards this variation, is perhaps appropriate. For example, of the 92 annual events on Fig. 2.18, only 55 (60%) involved a deviation in rainfall (measured as a % of the median) which was accompanied by a more extreme deviation, in the same direction, of run-off. Thus, the relatively high variation in annual water-year run-off in percentage terms, is not generally coincident with rainfall variation, but does tend to be so for the most extreme events.

#### 2.6.5.2 Recurrence Probabilities of Events During the 1971-76 Period

The foregoing probability distributions and cumulative probability curves have been used to calculate the recurrence probabilities of the severest rainfall and run-off events of various durations during the recent drought period, which are summarised in Table 2.4.

Once again, the special significance of 2 to 3-year periods is shown. For example, the 2-year rainfall (1971/2 - 72/3) and the 3-year run-off (1971/2 - 73/4) have calculated annual recurrence probabilities of 0.004. The corresponding return period, of 250 years, would seem to be a reasonably reliable estimate in that the concurrent rainfall events of similar durations were also the severest

over a 200-year record at Blackford Hill, 20km north of Gladhouse Reservoir.

TABLE 2.4 : Recurrence Probabilities of Severe Rainfall and Run-Off Events at Gladhouse During the Period 1971-76.

No. Years (D)	Water-year period (inclusive)	Annual Recurrence Probability	
		Rainfall	Run-Off
1	72/3	0.021	0.030
2	71/2 - 72/3	0.004	0.013
2	72/3 - 73/4	0.019	0.009
3	71/2 - 73/4	0.010	0.004
4	72/3 - 75/6	0.046	0.010
5	71/2 - 75/6	0.038	0.007
6	70/1 - 75/6	0.034	0.011

Also, the recurrence probabilities of run-off tend to be smaller than those for rainfall, especially for the longer periods under concern, thus indicating that the long duration run-off events were considerably more abnormal than the corresponding rainfall ones during the 1971-76 period.



It is perhaps pertinent at this point to compare the rainfall recurrence probabilities tabulated above with those quoted in Section 2.3.1, based on the Meteorological Office's use of the period of 1911-70. If the data for Blackford Hill, whose proximity to Gladhouse Reservoir is indicated above, are compared with those derived from the 92-year series, an interesting fact emerges. This is concerned with the fact that although recurrence probabilities of 1 and 2-year events are of a slightly higher order for the Gladhouse rainfall series, those concerned with 4, 5 and 6-year events are typically ten times greater for this 92-year data series. Thus, it would appear that probabilities of occurrence based on the 60-year period, in Section 2.3.1 are, at least in the case of Blackford Hill, underestimated quite seriously for periods greater than 3 years. This effect is no doubt associated with the exclusion of the 1971-76 period in the 1911-70 period used by the Meteorological Office in their probability analyses. Consequently, the usefulness of the recurrence probabilities based on this 60-year period, as shown in Fig. 2.5 must be subject to even further doubt.

Nevertheless, the extreme nature of the hydrometeorological and hydrological events in the East of Scotland during the 1971-76 period have been indicated in some detail. In particular, the 3-year <sup>run-off</sup>~~rainfall~~ and 2-year <sup>rainfall</sup>~~run-off~~ totals in the south-east of the country, over the water-year periods of 1971/2 - 1973/4 and 1971/2 - 1972/3 respectively, have estimated return periods of around 250 years.

It is for this and similar severe run-off events, that the following section analyses the direct and indirect drought impacts associated with low levels of flow in the watercourses of eastern Scotland during the 1971-76 period.

SECTION 3  
DROUGHT IMPACTS DURING  
THE 1971-76 PERIOD



### 3.1 INTRODUCTION

The previous section has described the nature of low river flows during the 1971-76 period, and over the long term. The purpose of this section is to consider the implications associated with man's activities and "demands" concerning water, in relation to the variable natural "supply" element above. For example, demands made on rivers such as sewage effluent discharges and water supply abstractions can significantly alter both the quantity and quality of flow in an affected watercourse, and especially so in conditions of low flow.

Such demands can conveniently be divided into two main practices, ie. water supply provision and waste water disposal. The latter part of this section deals with the former, and there now follows an investigation of the impacts of low flows on the second group of demands. This is done by use of typical examples, and a detailed study for one specific case. Most of the information presented describes river water quantities and qualities over the 1971-76 period, and where possible considers the impacts on aquatic life. However, only limited information is available as regards this last aspect of the drought, and consequently generalised assumptions have to be applied to most cases.

### 3.2 DROUGHT IMPACTS ASSOCIATED WITH WASTE WATER DISPOSAL

#### 3.2.1 River Water Quality 1971-76

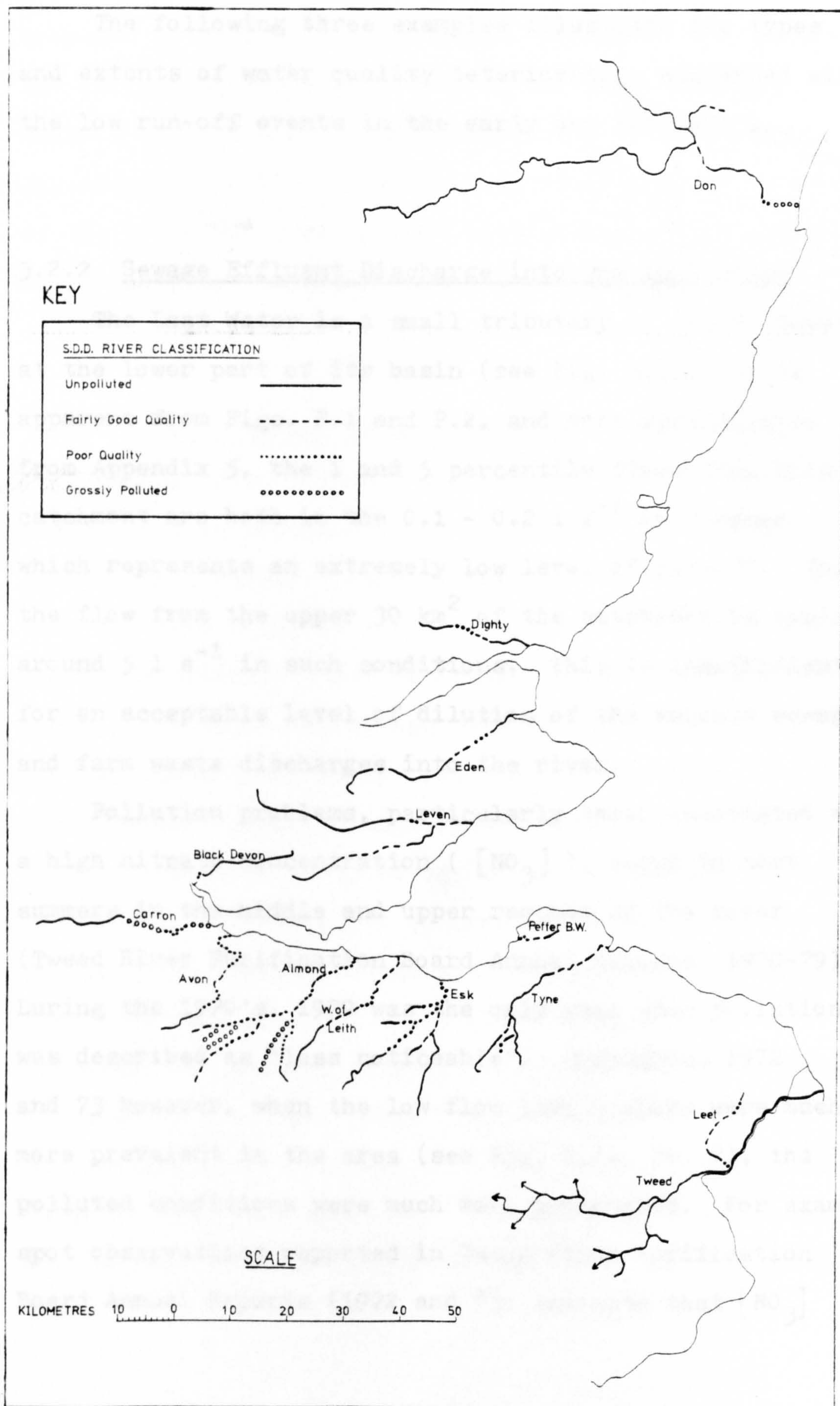
The responsibility for the systematic monitoring of the quality of inland waters in Scotland lies with the seven River Purfication Boards. These Boards generally make collected data available for public inspection. Personal communication with these bodies has revealed that significant problems concerned with a deterioration of river water quality directly attributable to the occurrence of low flows, were generally scarce during the 1971-76 period. Increased levels of pollutants only caused concern in rivers where pollution was to some extent an existing feature.

The extent and degree of river pollution in eastern Scotland in 1971 is indicated in Fig. 3.1, which is reproduced from a report by the Scottish Development Department (1972). Only those watercourses where waters of "poor quality" are apparent to some degree are included. This is because waters in the first two categories of "unpolluted" and "fairly good quality" tended to suffer no further deterioration in quality associated with low flows. Similarly, at the other end of the scale, "grossly polluted" watercourses generally remained in the same condition during the 1971-76 period. Therefore, it is principally those river stretches indicated to be of "poor quality" in Fig. 3.1 which are of the most interest.



**FIGURE 3.1 : Water Quality in Rivers with Stretches Of Poor Quality in the East of Scotland in 1971**

source : Scottish Development Department (1972)





The following three examples illustrate the types and extents of water quality deterioration concerned with the low run-off events in the early and mid-1970's.

### 3.2.2 Sewage Effluent Discharge into the Leet Water

The Leet Water is a small tributary of the R. Tweed at the lower part of its basin (see Fig. 3.1). As is apparent from Figs. F.1 and F.2, and more specifically from Appendix 5, the 1 and 5 percentile flows from this catchment are both in the  $0.1 - 0.2 \text{ l s}^{-1} \text{ km}^{-2}$  range, which represents an extremely low level of run-off. Thus, the flow from the upper  $30 \text{ km}^2$  of the catchment is typically around  $5 \text{ l s}^{-1}$  in such conditions. This is insufficient for an acceptable level of dilution of the various sewage and farm waste discharges into the river.

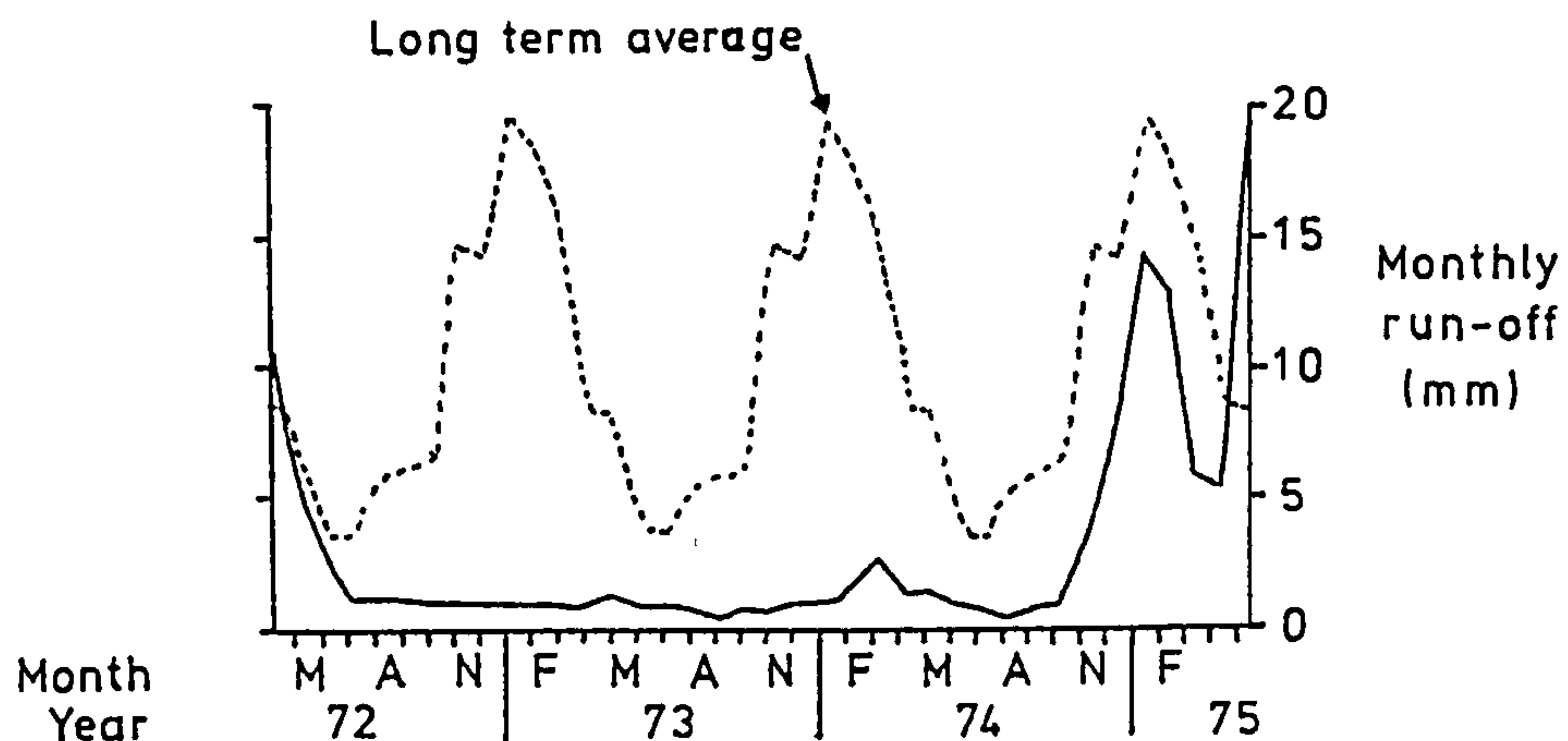
Pollution problems, particularly those associated with a high nitrate concentration ( $[\text{NO}_3]$ ), occur in most summers in the middle and upper reaches of the river (Tweed River Purification Board Annual Reports, 1970-79). During the 1970's, 1979 was the only year when pollution was described as "less noticeable". Throughout 1972 and 73 however, when the low flow levels above were much more prevalent in the area (see Fig. 2.14, No. 7), the polluted conditions were much more pronounced. For example, spot observations reported in Tweed River Purification Board Annual Reports (1972 and 73) indicate that  $[\text{NO}_3]$

exceeded  $10 \text{ mg l}^{-1}$  in these years, approximately double the maximum levels experienced in the more "normal" summers of 1978 and 79. In addition, dissolved oxygen was recorded to be zero at some locations, and many sections of the river bed were covered with sewage fungus (Tweed River Purification Board Annual Reports 1972 and 73).

### 3.2.3 Nitrate Levels in East Lothian Rivers

East Lothian includes some of the most productive arable land in Scotland (East of Scotland College of Agriculture, 1977a). Farming practice in the area requires that the land receives sizeable quantities of fertiliser, including nitrates (East of Scotland College of Agriculture 1977b). In addition, as has been shown earlier, this part of the country is an area where meteorological and hydrological events of the 1971-76 period were most abnormal, both in terms of magnitude and probability of recurrence. The level of abnormality was most pronounced in the small coastal catchments, such as that of the Peffer Burn West (see Fig. 3.1), for which the monthly run-off at Luffness, as compared with the estimated 1961-78 average is shown in Fig. 3.2. This figure reveals that 36 consecutive months of less than monthly average run-off began in May 1972, whereas on the larger R. Tyne nearby, the relevant duration was 24 months (see Fig. 2.10, No. 7).

FIG. 3.2 : Monthly Run-Off at Luffness on the Peffer Burn West 1972-75.



In these watercourses, the water quality parameter most affected was that of  $\text{NO}_3$  concentration. Annual extreme nitrate levels in  $\text{mg l}^{-1}$ , measured by the Forth River Purification Board for the above location on the Peffer Burn West, and another on the upper reaches of the R. Tyne at Ormiston are summarised in Tables 3.1 and 3.2.

For 1972 and 73 (and 74 at Luffness) both the minimum and maximum sampled levels of  $\text{NO}_3$  are relatively low. Indeed, there are instances at both locations where no detectable nitrate content was found. This can be associated with the very small quantities of soil water containing artificially-added  $\text{NO}_3$ , running off into the watercourses.



TABLE 3.1 : Extreme Recorded Nitrate Levels at Luffness on the Peffer Burn West 1971-76.

source : Forth River Purification Board.

Year	[NO <sub>3</sub> ] (mg l <sup>-1</sup> )	
	Minimum	Maximum
1971	2.8	14.0
72	1.1	14.0
73	0	2.7
74	0.2	3.7
75	0.4	15.1
76	0.1	24.0

TABLE 3.2 : Extreme Recorded Nitrate Levels at Ormiston on the River Tyne 1971-76.

source : Forth River Purification Board.

Year	[NO <sub>3</sub> ] (mg l <sup>-1</sup> )	
	Minimum	Maximum
1971	0	0.2
72	0	0.4
73	0	1.5
74	0.8	12.9
75	0.7	7.7
76	0.7	7.9

However, at the onset of the first appreciably high river flows after the dry period, which occurred later at Luffness, sampled  $\text{NO}_3$  levels rose significantly. For example,  $12.9 \text{ mg l}^{-1}$  was recorded at Ormiston in 1974, and  $15.1 \text{ mg l}^{-1}$  at Luffness the following year. The same pattern of events repeated itself in 1976. On 3.8.76 on the Peffer Burn West, the  $\text{NO}_3$  concentration was recorded at  $0.6 \text{ mg l}^{-1}$ , and on 19.10.76, following the dramatic end to the low flow period, a level of  $18.7 \text{ mg l}^{-1}$  was sampled.

It is of particular interest that these high  $\text{NO}_3$  concentrations occurred despite the fact that there was much more water available for their dilution than during the low flow periods. Such increased concentrations can be explained by the greater leaching of the relatively high levels of  $\text{NO}_3$  accumulated in the soil. It is not known whether fertiliser applications were made as normal during the dry periods, thus increasing the amount of nitrate in the soil, and exacerbating this effect.

The nitrate concentrations experienced are well above the Commission of the European Communities (1976) standard's of 3 and  $6 \text{ mg l}^{-1}$  for salmonid and cyprinid waters respectively. However, it is debatable whether the high  $\text{NO}_3$  concentrations experienced would be a limiting factor for the well-being of aquatic life, when streamflow itself had been so low for so long previously.

#### 3.2.4 Industrial and Sewage Effluents in the River Don

The pollution problem on the R. Don in the Grampian Region is restricted to the furthest downstream 6 km of a total river length of some 120 km (see Fig. 3.1). The sources of the pollution in this part of the river are the effluents of two paper mills, which between them dispose of about  $30,000 \text{ m}^3$  per day (40,000 in 1972) of waste, and that of Persley sewage works which serves a population of around 40,000 (North East River Purification Board, 1980).

In times of low flow, apart from the obvious possibility of a lack of adequate dilution, there are the added problems associated with sewage fungus in that part of the R. Don downstream from the effluent discharges. This filamentous bacteria can have a relatively high Biological Oxygen Demand (B.O.D.), and its existence and growth tends to be more influenced by river flow than temperature (Sanders, 1980). It is considered that a temperature of around  $15^\circ\text{C}$  is required to initiate a season's growth, which is maintained by temperatures above  $10^\circ\text{C}$ . However, the filaments which can grow to about 100mm in length are broken off down to c. 25mm in spate conditions. For this purpose, a spate can be defined as a rapid rise in river flow exceeding  $5 \text{ m}^3 \text{ s}^{-1}$  (Sanders, 1980).

In low flow conditions, very low dissolved oxygen (D.O.) levels can occur. For example, the European Inland Fisheries Advisory Commission (1973) report that in 1971,



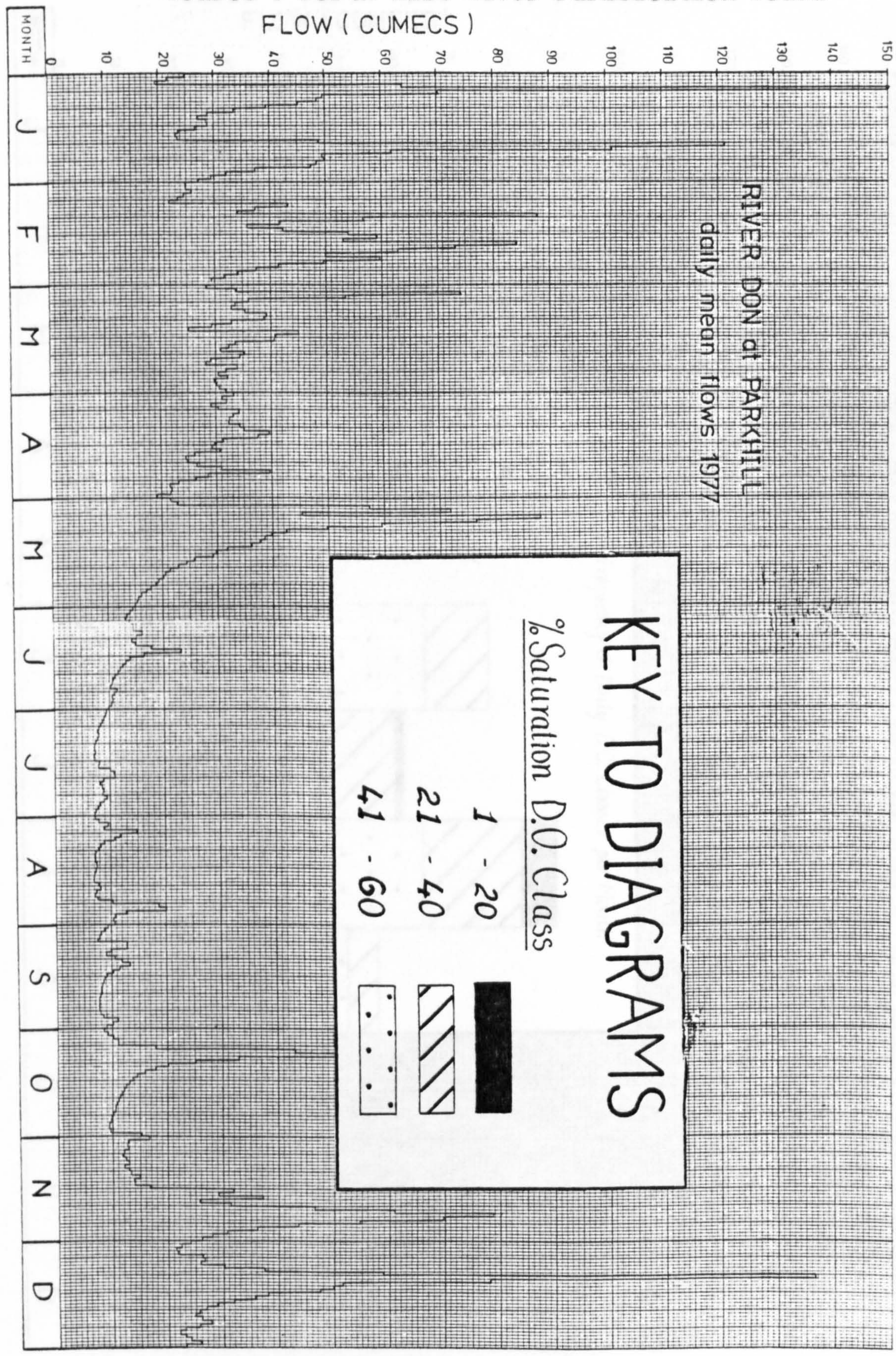
at temperatures of 18-23°C and D.O. levels of about 4 mg l<sup>-1</sup>, a heavy mortality of salmon (Salmo salar) occurred in the R. Don. Consequently the North East River Purification Board (N.E.R.P.B.), (1980), have set a desirable minimum D.O. level of 60% saturation (the equivalent of 6 mg l<sup>-1</sup> at 15.6°C, but only 5 mg l<sup>-1</sup> at 24°C. Since this latter water temperature is around the highest ever experienced, then the 60% saturation standard can be associated with an absolute minimum D.O. level of 5 mg l<sup>-1</sup>.

During the period 1971-76, flow conditions were such that D.O. levels beneath the 60% saturation limit occurred each summer. The three annual hydrographs of daily mean flow for the years 1977, 76 and 72, shown in Figs. 3.3.1 to 3.3.3, can be used to illustrate the effects of low flow on critical D.O. levels. The flow data refer to the N.E.R.P.B. gauging station at Parkhill, only 5 km upstream of the site of effluent discharges. Superimposed on the hydrographs of 1976 and 72 are histograms depicting the frequency of occurrence of classes of D.O. % saturation values on a monthly basis, the key for which is included in Fig. 3.3.1. The classification used indicates the level of incidence of values in the ranges 1-20, 21-40 and 41-60% saturation. The daily D.O. data used were recorded by the N.E.R.P.B. at Grandholm Bridge, downstream of Parkhill by 7 km, over which distance only very minor tributaries enter the R. Don. Thus, the flow data can be used quite confidently to estimate the flow at Grandholm Bridge.



FIGURE 3.3.1 : Hydrograph of Daily Mean Flows at Parkhill on the R. Don in 1977 and Key to D.O. Saturation Classification

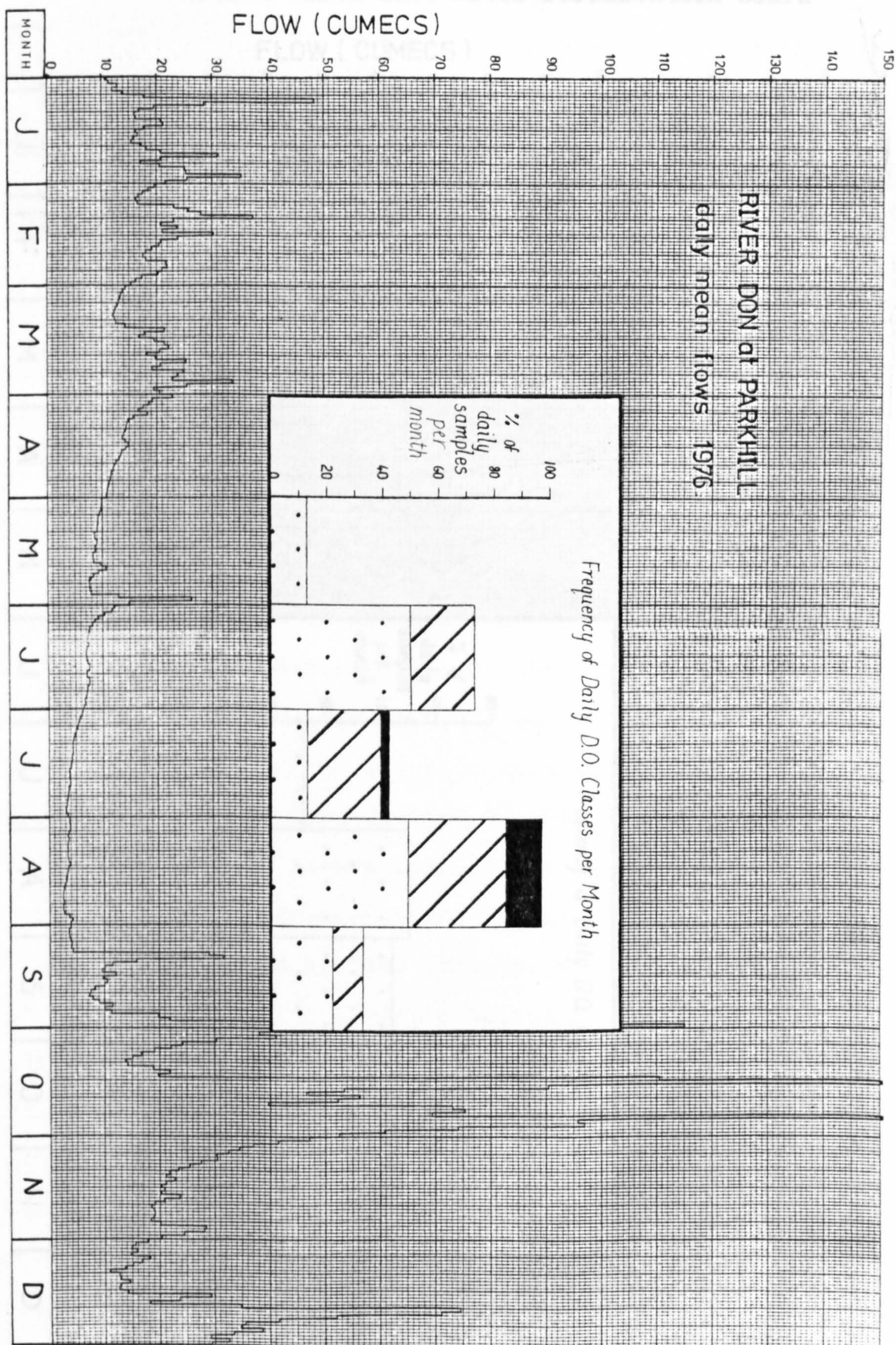
Source : North East River Purification Board





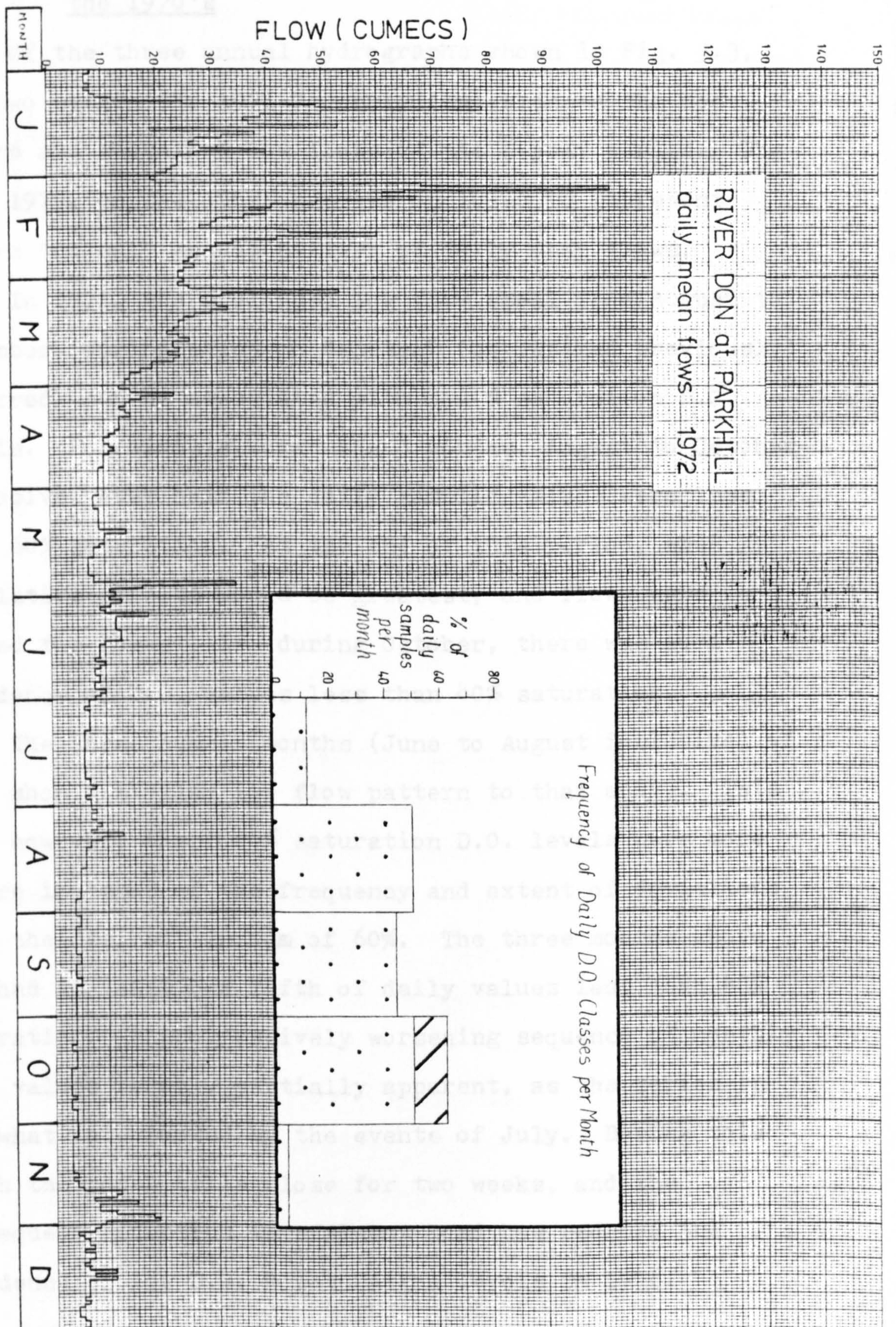
**FIGURE 3.3.2 : Hydrograph of Daily Mean Flows at Parkhill  
on the R. Don and the Monthly Frequency of L<sub>a</sub>  
Daily D.O. Saturation Levels for 1976**

**Source : North East River Purification Board**





**FIGURE 3.3.3 : Hydrograph of Daily Mean Flows at Parkhill  
on the R. Don and the Monthly Frequency of  
Low Daily D.O. Saturation Levels for 1972**  
 Source : North East River Purification Board





#### 3.2.4.1 The Effects of Flow and Temperature on D.O. in the 1970's

Of the three annual hydrographs shown in Fig. 3.3, the two within the 1971-76 period experienced the most severe and sustained low flows of the 6-year period. The year 1977, on the other hand is included to represent a more "normal" annual pattern of daily mean flows.

In 1972, the prolonged low flow spell from August to November, during which no "spates" (as defined previously) occurred, can be associated with low % saturation D.O. levels. For example, over the 3 months, August to October inclusive, over half the daily sampled values were less than 60% saturation. At the end of this period, when cumulative effects would be greatest, and flows were indeed the lowest, ie. during October, there was some incidence of D.O. values less than 40% saturation.

The three summer months (June to August inclusive) of 1976 show a similar low flow pattern to that above. This time however, the low % saturation D.O. levels were more severe in terms of the frequency and extent of deviations from the desired minimum of 60%. The three months above all had at least one fifth of daily values less than 40% saturation. A progressively worsening sequence of monthly D.O. values is only partially apparent, as the series is somewhat interrupted by the events of July. During this month the paper mills close for two weeks, and the consequent reduction in effluent load has reduced the incidence of low D.O. % saturation levels in 1976.

The year 1977 in fact involved no D.O. levels of less than 60% saturation. Indeed, the lowest recorded value was 74%. This is because, firstly, flows over the lowest run-off period (July to September inclusive) were typically twice those of the low flow periods of 1972 and 1976, thus increasing dilution of effluents. Secondly, there were at least 3 "spates" during this period, which would disrupt the growth of sewage fungus.

Although the low flow events of 1972 and 1976 were similar in nature, they resulted in considerably different distributions of daily D.O. levels over the months concerned. This variation is best explained by the higher ambient temperatures prevalent during the relevant months of 1976. Although mid-summer temperatures can normally be expected to be higher than those of late summer/autumn, in addition, such temperatures were above average in 1976. For instance, the Meteorological Office (1977) report that, in 1976 daily mean air temperatures were 2.6 and 1.7°C respectively above the 1941-70 July and August averages at Dyce, only 5 km north of study area. These increased temperatures will most probably have resulted in more proliferate growth of sewage fungus, hence greater B.O.D.'s and lower % saturations of D.O. It is worth noting here that the use of % saturation measures of D.O. eliminates any consideration of the variation of the solubility of oxygen in water due to differences in temperature. Therefore the reductions in % saturation D.O. must be caused by the indirect biological factors above.



Consequently, it would appear that due to both physical and biological effects of temperature variation, an autumnal low flow period is markedly less severe than one in summer, as regards D.O. levels in  $\text{mg l}^{-1}$ , in the furthest downstream stretch of the R. Don. However, the relative comparison of impacts is dependent on the timing of demands placed upon D.O. levels in this part of the river. More specifically, this depends on the seasonal habits of the migratory fish such as salmon, which travel up through the mouth of the R. Don.

### 3.3 SEWAGE EFFLUENT DISPOSAL IN THE RIVER ALMOND

#### 3.3.1 Introduction

The foregoing examples have shown the types of chemical and biological changes in the watercourses in the East of Scotland associated with the low flows experienced during the 1971-76 period. In addition some indications of the possible environmental impacts on fishery interests have been given.

It would be most useful to attempt to quantify any relationships between river flow, the water's chemical status, and any associated biological impacts by means of a predictive model. Indeed, the North East River

Purification Board are presently collecting data to allow such an investigation of the situation on the R. Don, which has been summarised earlier. However, an adequate store of water quality and flow data, which would support the construction of a predictive model, ~~was~~<sup>were</sup> found to exist for the R. Almond in West Lothian. The following pages describe the nature of the pollution problem in this river, and how the relevant data was employed to form a model to predict water quality status.

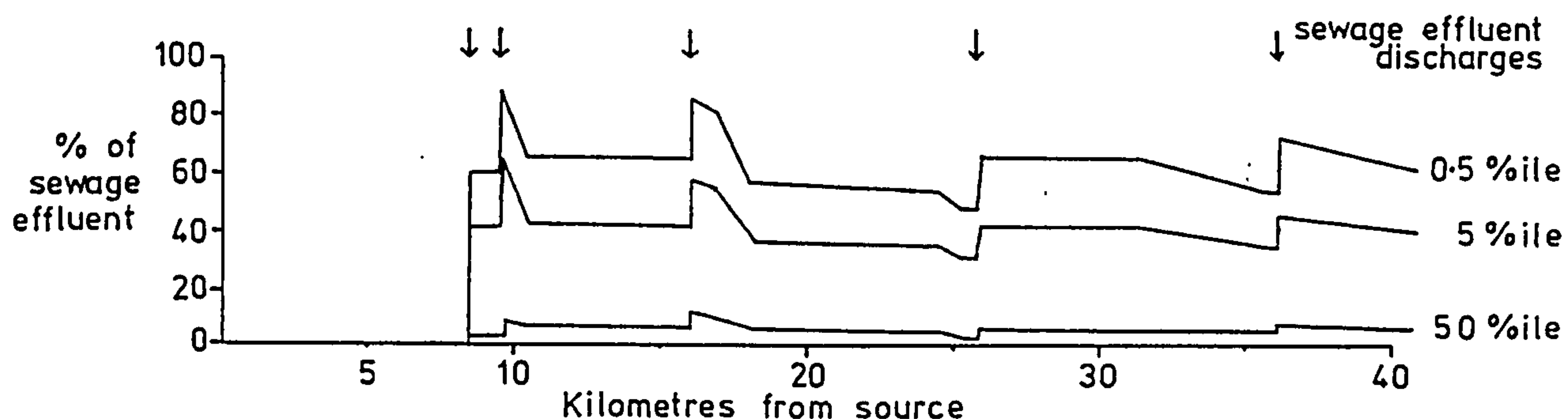
### 3.3.2 General Background

The R. Almond in 1971 was polluted to varying degrees in different reaches, as Fig. 3.1 indicates. Along the 42 km length of the main watercourse, there are 5 sewage works, whose total "dry weather" effluent outflow is around  $300 \text{ l s}^{-1}$  (Forth River Purification Board, 1974). The magnitude of the various discharges is such that there is a gradual increase from works to works in a downstream direction. The percentage of sewage effluent in the river at three different flow levels, based on Forth River Purification Board (1974) figures is shown in Fig. 3.4.

At long term (1961-78) average flows, the proportion of sewage effluent in the river hardly rises above 10%. At lower flows, this proportion is substantially higher. For instance, at the 5 percentile level, typically 40% of the water all along the river downstream of the first

sewage works is sewage effluent. At the 0.5 percentile flow, this figure rises to 60%.

FIGURE 3.4: Percentages of Sewage Effluent Along the R. Almond at Three Percentile Flow Levels

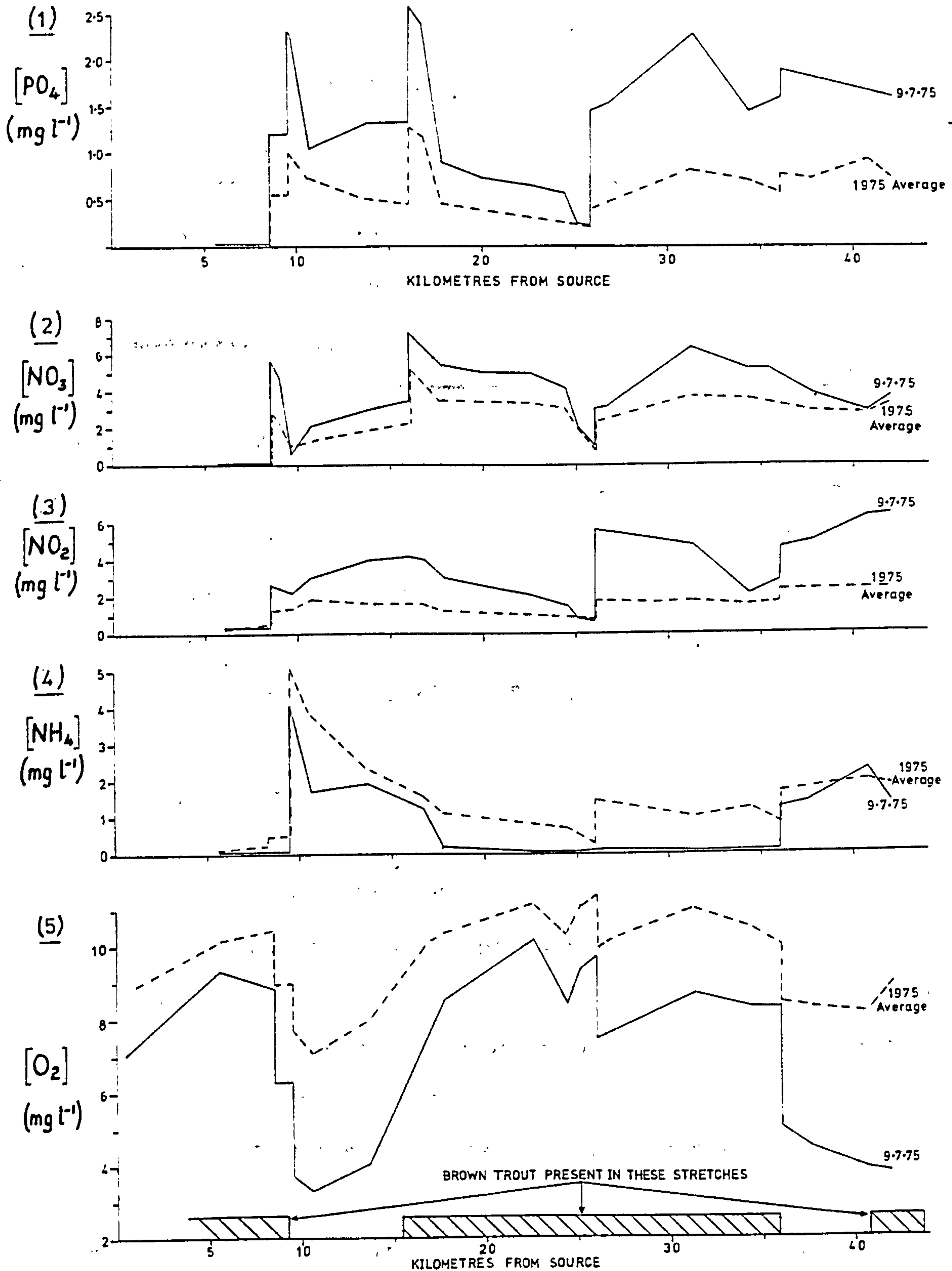


The Forth River Purification Board (F.R.P.B.) carries out routine chemical analyses (about 15 per year) for each of 18 locations along the R. Almond. The lowest flows ever sampled occurred on 9.7.75. On this day, the discharge of  $554 \text{ l s}^{-1}$  at Craigiehall gauging station on the lower part of the river corresponded closely to the 0.5 percentile flow. Various parameters of water quality measured on this date are compared with average values for 1975 (a year of relatively high incidence of low flows as shown in Fig. 2.14, No. 6), on Fig. 3.5. The five measures of chemical pollution which can be associated with sewage effluent are now considered individually, with reference to Fig. 3.5.

(1) Phosphate ( $\text{PO}_4$ ) concentrations on 9.7.75 were consistently 2 to 3 times higher than the 1975 average figures.



**FIGURE 3.5 : Concentrations of Five Water Quality Parameters  
Along the R. Almond on 9.7.75 and Average Values  
for the Year 1975**



(2) Nitrate ( $\text{NO}_3$ ) levels were all higher than the average values, but always by a factor less than 2.

(3) Nitrite ( $\text{NO}_2$ ) levels were once again consistently higher on the date of low flow, by a factor of up to 3 over the 1975 averages.

(4) Ammonia ( $\text{NH}_4$ ) concentrations were typically less than the 1975 average on 9.7.75. The reduction was most noticeable in the normally less-polluted stretches of the river.

(5) Dissolved Oxygen concentrations, in  $\text{mg l}^{-1}$ , were all lower than the 1975 average values on the date in question, and in the most extreme cases were less than half this value. Indeed, the F.R.P.B. (1975) reported that "sewage effluent was producing conditions of critically low oxygen tension during low summer flows", thus indicating the particular severity of low D.O. levels.

The notable range of variation in conditions over the 18 chemical sampling stations indicates that although the proportion of sewage effluent is remarkably constant along the river, the quality of individual effluents varies considerably. The general pattern of events shown on Fig. 3.5 is that stretches of the river which are relatively more polluted over the average conditions become proportionally even more polluted in low flow conditions. For example, for the locations where water quality is normally most unfavourable, the concentrations of  $\text{PO}_4$ ,  $\text{NO}_3$  and  $\text{NO}_2$  generally underwent a greater increase from average on 9.7.75.

D.O. levels similarly suffered a proportionally higher reduction from average values. In keeping with this pattern, the reductions in  $[\text{NH}_4]$  were proportionately lower for the relatively more polluted locations on the R. Almond.

### 3.3.3 Requirements for a Predictive Model of Water Quality

It has been indicated that low flow conditions can have a marked association with variation in different measures of pollution and that it would be most useful to quantify any relationships, and incorporate them in a predictive model. This would allow an assessment to be made of water quality for any given flow conditions, at any time.

The first step in this procedure should be to assess the homogeneity of data concerning relevant contributory factors. Unfortunately, data on effluent quality are confidential. However, inferences can be made from changes in methods of treatment, and the quantities involved. F.R.P.B. Annual Reports covering the period 1971-76 reveal that during these 6 years;

- (i) no major new sewage works developments were commissioned;

- (ii) effluents from one works, namely Newbridge, were given improved treatment;

- and (iii) the quantity of sewage being treated increased slightly, eg. the largest annual increase of 2% was recorded between the years 1973 and 74.



It is considered that such relatively minor variations over the 1971-76 period can justifiably be disregarded, and that sewage effluent conditions can be assumed to be constant over the period. In any case, the effects of (ii) and (iii) above may cancel each other out to some extent.

A further complication is introduced by the wide range of conditions of various water quality parameters prevalent over the length of the R. Almond, and the various effects low flows seemingly have in different locations. For example, as Fig. 3.5 indicates, on the low flow of 9.7.75, the "poor quality" stretch 40 km from source encountered  $\text{NH}_4$  concentrations similar to the 1975 average. However, only 10 km upstream in waters of "fairly good quality",  $\text{NH}_4$  fell to one-tenth of the 1975 average. Thus, it was decided to restrict the predictive model to one particular sample site. That at Cramond Bridge at the downstream extreme of the R. Almond was chosen for the following reasons;

- (i) its proximity to Craigiehall gauging station (1.5 km upstream) allows an accurate estimate of streamflow to be made;

- (ii) its considerable distance from any one particular source of sewage effluent and special influence it may have on water quality;

- (iii) the detrimental changes in the various indices of pollution are very noticeable in low flows (as on 9.7.75) in relation to other locations;

(iv) the possible effects of pollution on aquatic life. Firstly, brown trout (Salmo trutta) are present (F.R.P.B., 1980) as Fig. 3.5 (5) indicates. Secondly, migratory sea trout (Salmo trutta) are known to travel through this part of the river, as it is a popular angling area for such fish (Almond Angling Association, 1980).

#### 3.3.4 Model Formulation for $\text{PO}_4$ , $\text{NO}_3$ , $\text{NO}_2$ , $\text{NH}_4$

Over the 1971-76 period, the F.R.P.B. made 90 chemical analyses of water quality at Cramond Bridge. These included measurements of  $\text{NO}_2$ ,  $\text{NO}_3$ ,  $\text{NH}_4$  and D.O. concentrations, and water temperature. Information on  $\text{PO}_4$  concentration is available for 40 sampling dates.

The mean daily flow values at Craigiehall on the corresponding day to sampling were used to correlate, on logarithmic scales, streamflow and the levels of the various measures of pollution. The results shown in Figs. 3.6 to 3.10 are discussed below for each of the chemical parameters considered, except D.O.

#### $\text{PO}_4$

Generally speaking, there is a well-defined inversely proportionate relationship between flow and  $\text{PO}_4$  concentration, as shown on Fig. 3.6. The correlation coefficient ( $r$ ) is 0.91, which means that  $r^2$  (83%) of the variation in  $[\text{PO}_4]$  can be explained by the quantity of flow. The relationship



is not so clear at the extreme high flow end, but it is suspected that this could be associated with the difficulties involved in accurately measuring concentrations of  $0.1 \text{ mg l}^{-1}$  or less.

### NO<sub>3</sub>

Despite the situation on the low flow of 9.7.75 along the whole river, where NO<sub>3</sub> concentrations were relatively high, Fig. 3.7 would indicate differently. Indeed, as no discernable relation is apparent between [NO<sub>3</sub>] and flow at Cramond Bridge it appears that these are quite independent variables.

### NO<sub>2</sub>

There is a recognisable relationship between [NO<sub>2</sub>] and flow as Fig. 3.8 illustrates. The correlation coefficient of 0.86 indicates that 74% of the variation in NO<sub>2</sub> concentration can be attributed to variation in flow. There is, however, a wide range of possible nitrite concentration at each level of flow and therefore, the relationship cannot be considered to be very precise.

### NH<sub>4</sub>

Contrary to the R. Almond's overall pattern of variation of [NH<sub>4</sub>] in relation to low flow as shown in Fig. 3.5. (4), at Cramond Bridge it seems that there is a slight tendency for NH<sub>4</sub> concentrations to decrease as flow increases, as shown

FIGURE 3.6 : The Relation Between Flow and  $\text{PO}_4$  Concentration at Cramond Bridge on the R. Almond

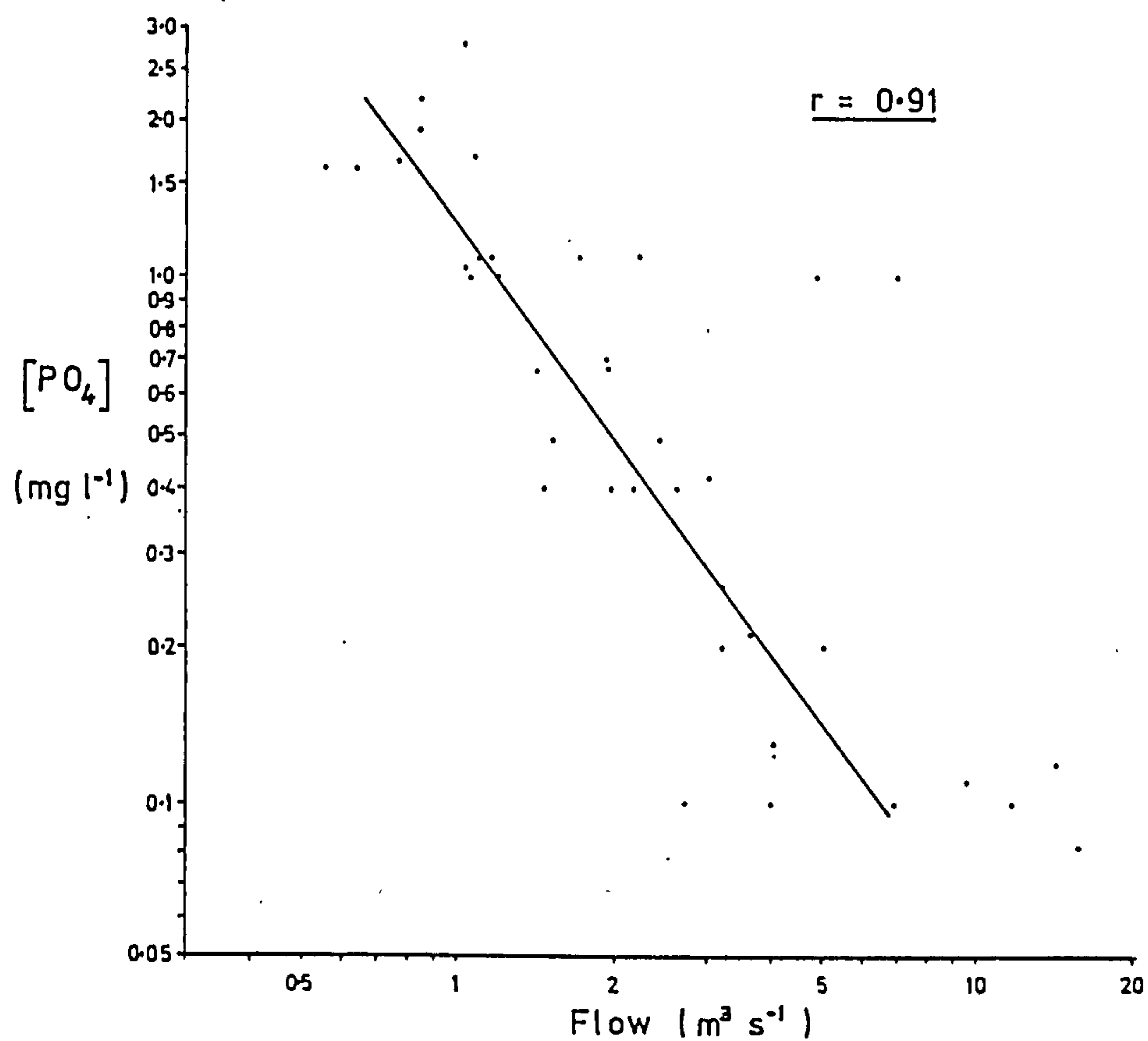
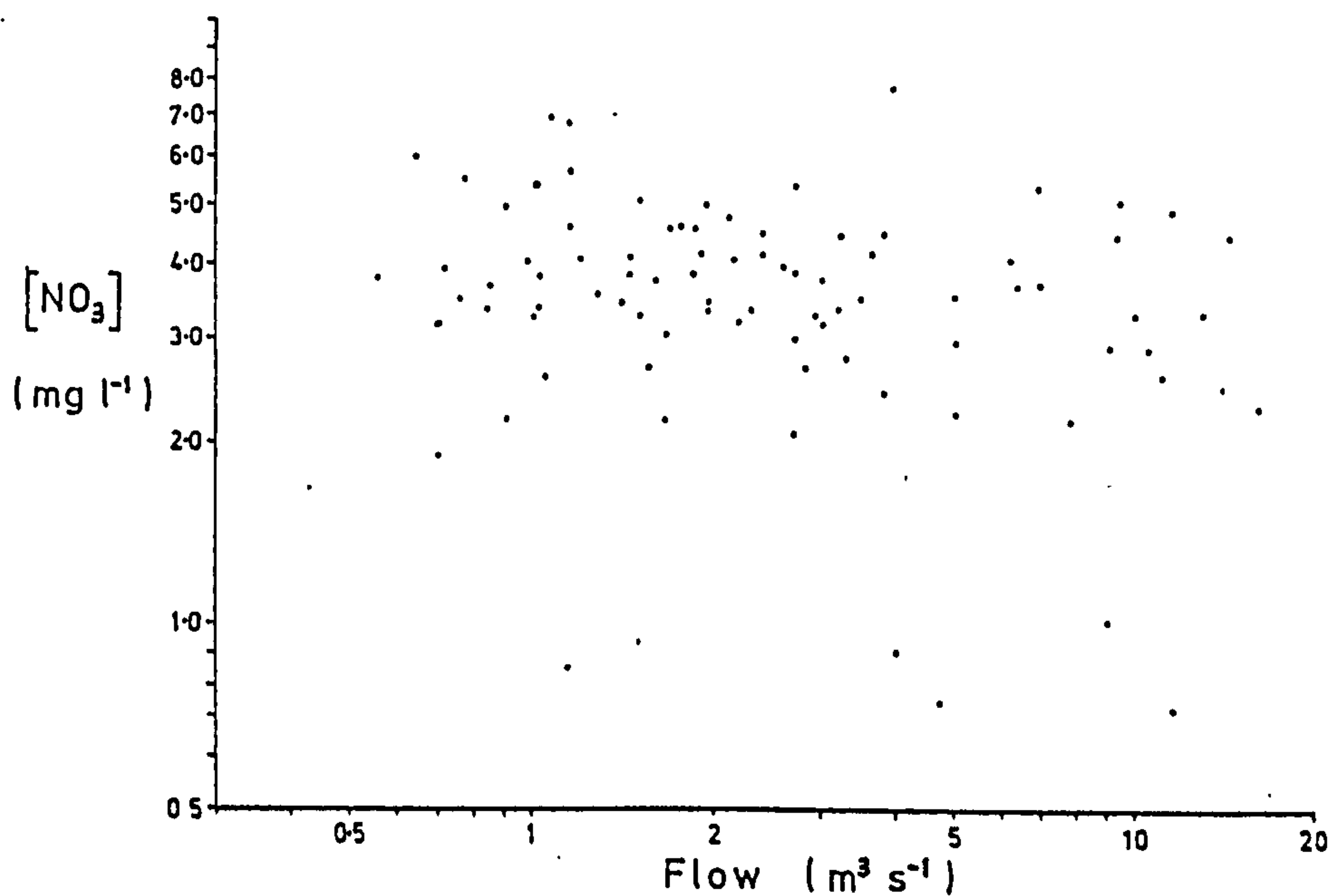
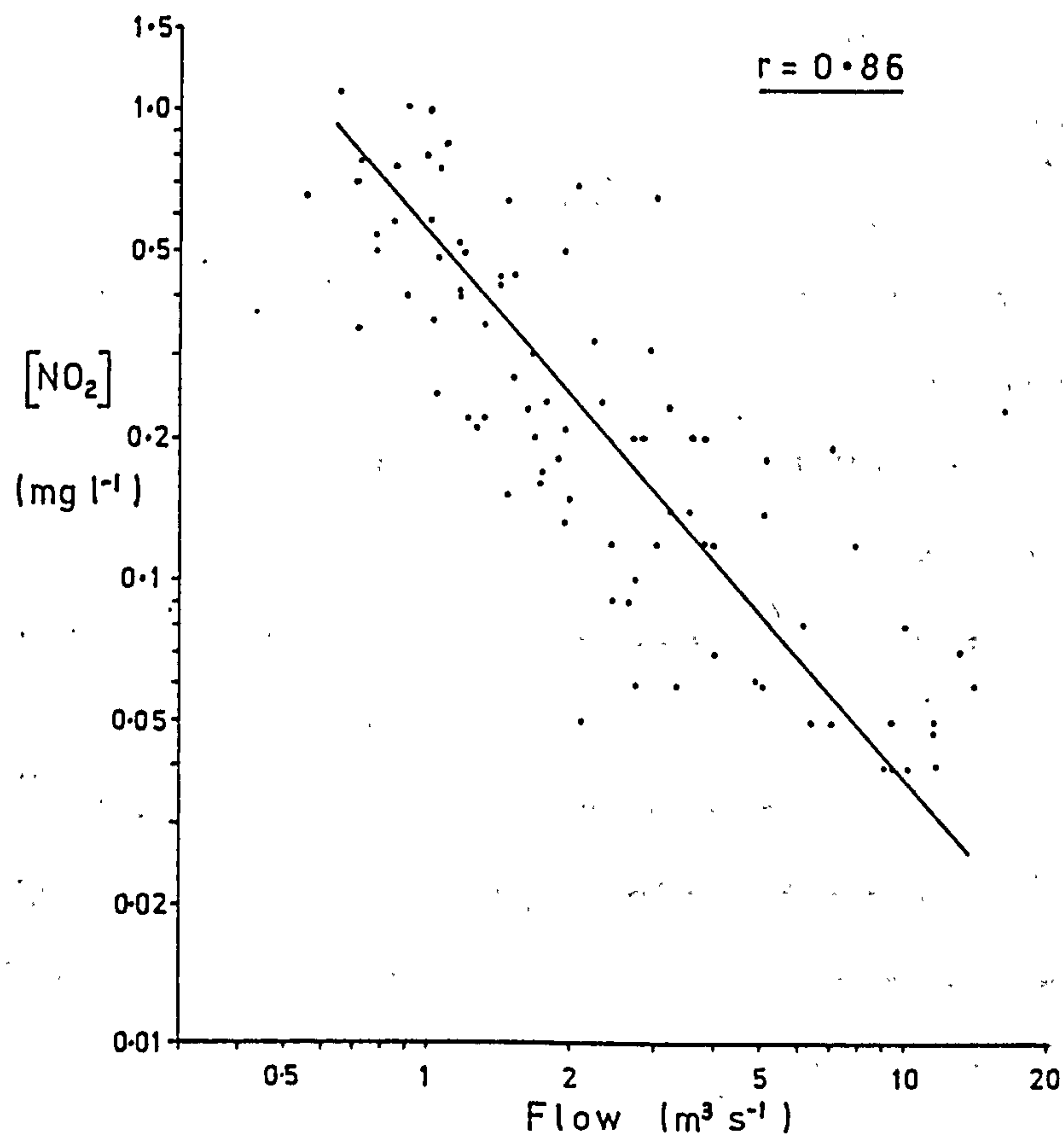


FIGURE 3.7 : The Relation Between Flow and  $\text{NO}_3$  Concentration at Cramond Bridge on the R. Almond

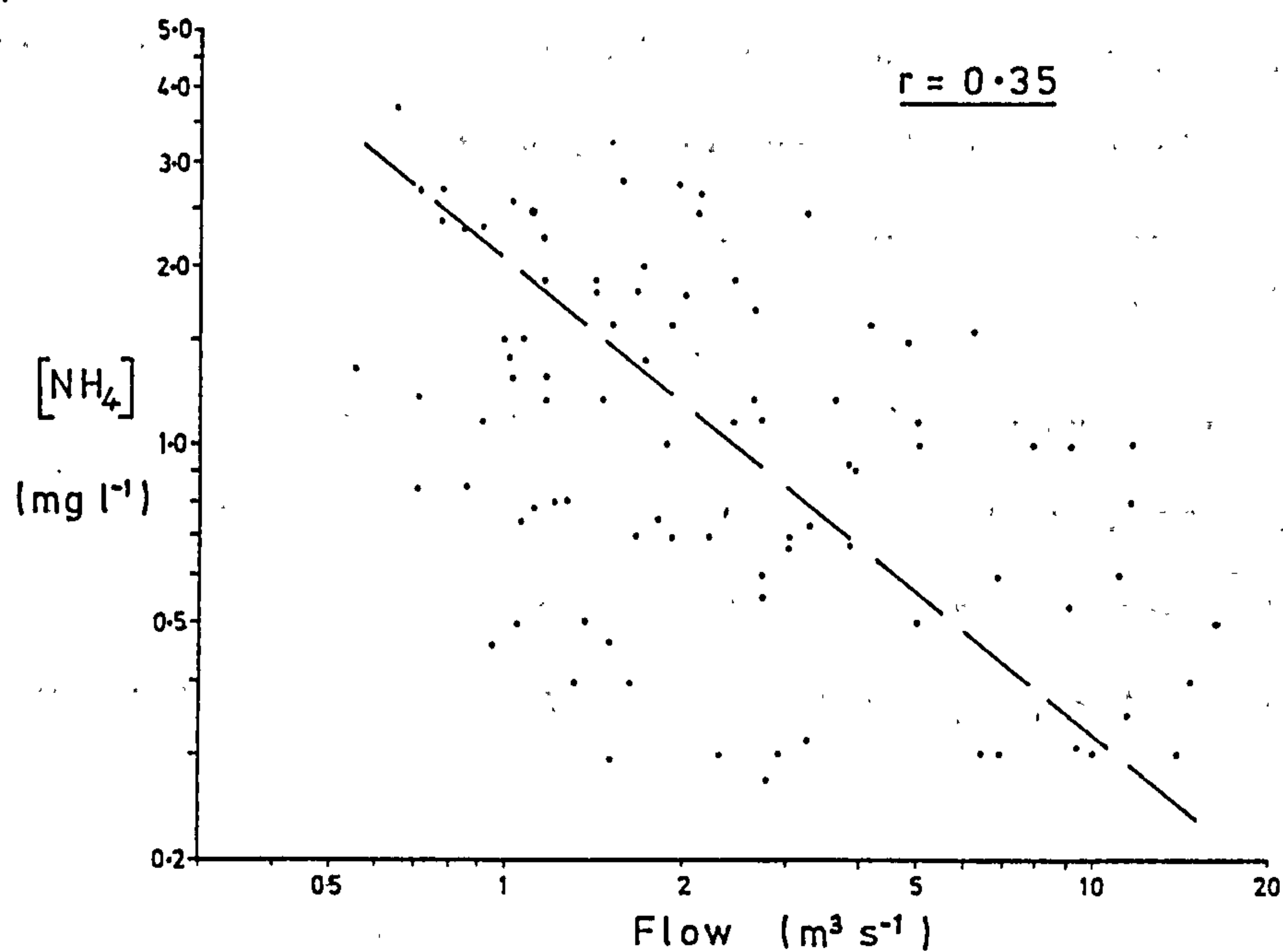




**FIGURE 3.8 : The Relation Between Flow and NO<sub>2</sub> Concentration**  
**at Cramond Bridge on the R. Almond**



**FIGURE 3.9 : The Relation Between Flow and NH<sub>4</sub> Concentration**  
**at Cramond Bridge on the R. Almond**



in Fig. 3.9. However, use of flow data can only explain 12% of the variation in ammonia levels.

This apparent anomaly probably has similar causes to that concerning nitrous nitrogen ( $\text{NO}_3$ ). The explanation could lie in the fact that the process of oxidation in a river downstream of a sewage effluent discharge converts  $\text{NH}_4$  to  $\text{NO}_3$ . Both Bartsch (1948) and Hynes (1963) have described this general effect, whereby, as the ammonia concentration gradually decreases downstream of the sewage effluent outlet, the nitrate concentration increases for a distance, and then further downstream, both concentrations tend to decline due to increasing dilution.

The situation on the R. Almond is that the sequence of five separate sewage effluent discharges (whose positions are shown on Fig. 3.4) complicates the above pattern of  $\text{NH}_4$  and  $\text{NO}_3$  concentrations, and also the effects of low flows on water quality along the river. Further complexities are added by the fact that whereas some sewage effluent discharges can be associated with the above effect, others cannot, as Fig. 3.5 shows. The most likely explanation is that the quality of the effluent varies from outlet to outlet.

There is also the possibility that unexplained variation could be attributable to other sources of nitrate, such as run-off from fertilised agricultural land. The relevant effects have been discussed in Section 3.2.3 for streams in East Lothian.

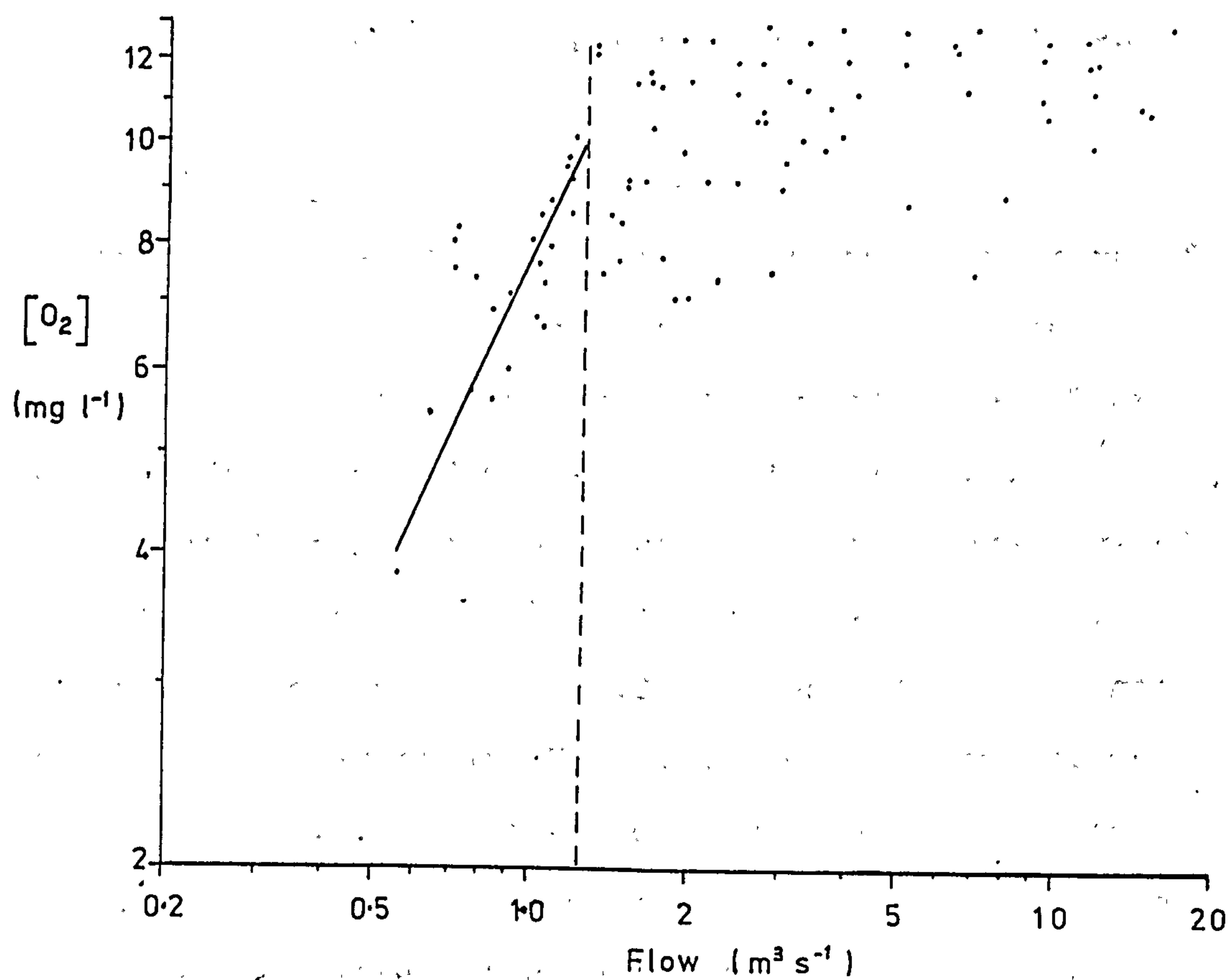


### 3.3.5 D.O. Model Formulation

As Fig. 3.10 illustrates, the relationship between D.O. ( $\text{mg l}^{-1}$ ) and flow is more complex than those discussed for the various nutrients. If a somewhat arbitrary point of separation is included, two distinct types of relation are obvious. At flows above the cut-off point of  $1250 \text{ l s}^{-1}$  (corresponding closely to the 15 percentile level) it would appear that any D.O. value between 7 and  $13 \text{ mg l}^{-1}$  is possible over nearly the whole range of flow. For flows less than  $1250 \text{ l s}^{-1}$ , there is a reasonably well-defined relation with D.O. at Cramond Bridge. For the 24 samples in this category of flow, the correlation coefficient for the two variables is 0.82. This means that two-thirds (67%) of the variation of the dependent variable, D.O., is explained by the relationship illustrated on Fig. 3.10.

Whilst the above relation is by no means useless, it was decided to attempt to develop a more precise relationship, since D.O. would appear to be the most important water quality parameter regarding the survival and well-being of aquatic life. There is ample evidence to support this contention. Downing and Merkins (1957) suggest that sewage effluents in themselves, are often only slightly toxic to fish, but indirectly, as a result of bacterial oxidation, they may have a profound effect by reducing D.O. to a point at which fish are asphyxiated. Judging by the specific concern of the F.R.P.B. (1975) about the effect of sewage effluent discharges on D.O. in low flow conditions quoted earlier in Section 3.3.2, this would seem to be the

**FIGURE 3.10 : The Relation Between Flow and Daytime Dissolved Oxygen Concentration at Cramond Bridge on the R. Almond**





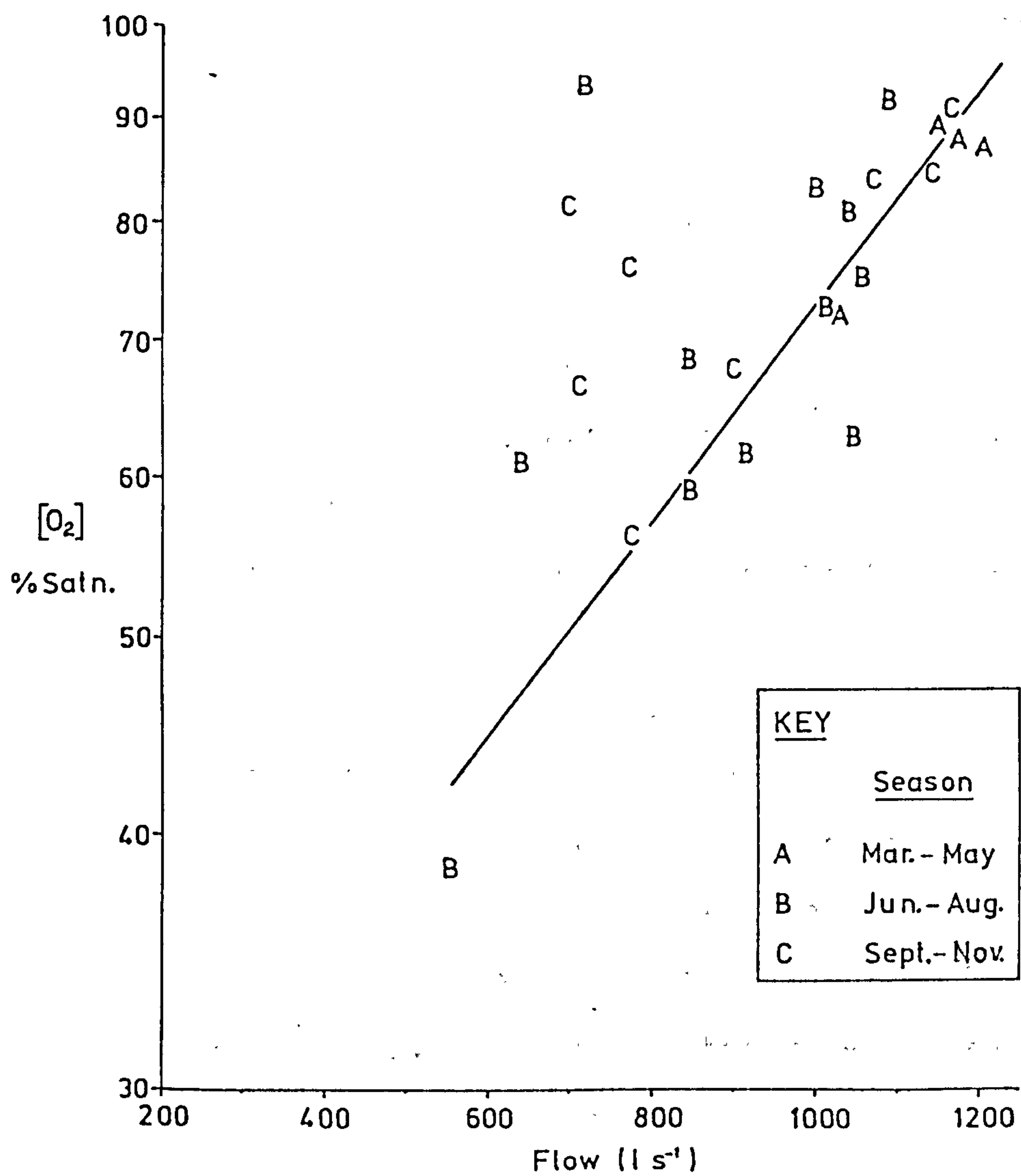
case for the R. Almond. Direct evidence for the dominant influence of D.O. on the well-being of the R. Almond fishery is provided by Fig. 3.5. (5), which clearly demonstrates that the distribution of brown trout along the river is more closely linked with that of D.O. conditions, rather than any other water quality parameter. For example, the presence of this species directly corresponds to those areas where the 1975 average D.O. exceeded  $8.5 \text{ mg l}^{-1}$ .

In order to construct a better-defined predictive model for D.O., the following variables were considered.

#### 3.3.5.1 Diurnal Variation of D.O.

Firstly, it was suspected that a possible pattern of diurnal variation of D.O. would render samples taken at different times of the day somewhat incompatible. There is definite evidence of a 24-hour pattern of D.O. variation at Cramond Bridge, similar to that investigated by Owens and Edwards (1964) in the sewage-polluted R. Anker in Cambridgeshire, such that D.O. concentration is higher by day and lower at night (F.R.P.B., 1980). Indeed, one particular F.R.P.B. investigation has revealed that in July, D.O. levels can fall to about  $1 \text{ mg l}^{-1}$  just before dawn. However, between the hours of 10a.m. and 3 p.m. there is no evidence of any significant change in D.O. Since all 24 samples of interest were taken during this period, then any influences of diurnal variation would be negligible.

**FIGURE 3.11 : The Seasonal Characteristic of the Relation Between Low Flows and Daytime Dissolved Oxygen Concentration at Cramond Bridge on the R. Almond**





#### 3.3.5.2 Seasonal Variation of D.O.

It is possible that photosynthetic activity, which in this part of the R. Almond is largely associated with algae (F.R.P.B., 1980), has a detectable seasonal influence on D.O. levels, as well as the above diurnal one.

To remove the effect of temperature on the solubility of oxygen in water, % saturation D.O. was plotted against flow for the 24 samples, for which the season of occurrence was noted. From the resulting Fig. 3.11, the only firm conclusion to be made is that the months September to November inclusive display a tendency to have higher than expected % saturation D.O. Levels. For example, of the 8 samples taken during this period, 6 had D.O. values greater than that predicted by the general line of relation.

Although this feature is considered worth noting, it is thought that the temporal division into seasons is too generalised, and that use of more specific variables would be more appropriate.

#### 3.3.5.3 Effects of Temperature and Sunshine

The relevant effects of temperature can be complex, as Hynes (1963) indicates. The rate of de-oxygenation, caused by bacterial breakdown of organic matter, can be influenced by temperature conditions. So too can the rate of re-oxygenation, which is dependent on the amount of photosynthesis, and is thus influenced by both temperature and sunshine. By incorporating these two variables, it is possible that a more satisfactory D.O. model can be achieved. In the

following analysis, the F.R.P.B. records of water temperature taken for the 24 sample flows are used, along with sunshine data from Turnhouse Airport (2 km south-west of the R. Almond at Cramond Bridge).

A straightforward correlation of either temperature, or say, sunshine hours with D.O. values would be misleading. This is because these factors themselves could be expected to have a reasonably strong association with the major independent variable ie. flow. Thus, the main problem concerned with measuring the influences of these further two factors on D.O. concentration is the removal of the effect of flow.

This difficulty can be overcome by examining D.O. levels occurring during flows which fall within a small and well-defined range. The chosen range of 1000 to 1100  $\text{l s}^{-1}$ , centred around the 10 percentile value of 1050  $\text{l s}^{-1}$ , allows the examination of eight sample measurements. The inherent variation in D.O. over this range of flow is  $\pm 0.2 \text{ mg l}^{-1}$ , as can be seen from the line of relation on Fig. 3.10, and is considered to be negligible.

Fig. 3.12 shows the eight water temperature values plotted against % saturation of D.O. This measure is preferred to that of  $\text{mg l}^{-1}$  at this stage, since it removes the physical effects of temperature on the solubility of oxygen. Initially, there would appear to be no obvious or useful relationship. However, if a measure of "sunshine" is included, the situation is clarified. A very simple

FIGURE 3.12 : The Relation Between % Saturation Daytime D.O. and Water Temperature, for Both Dull and bright Conditions, at Flows Around the 10 Percentile at Cramond Bridge on the R. Almond

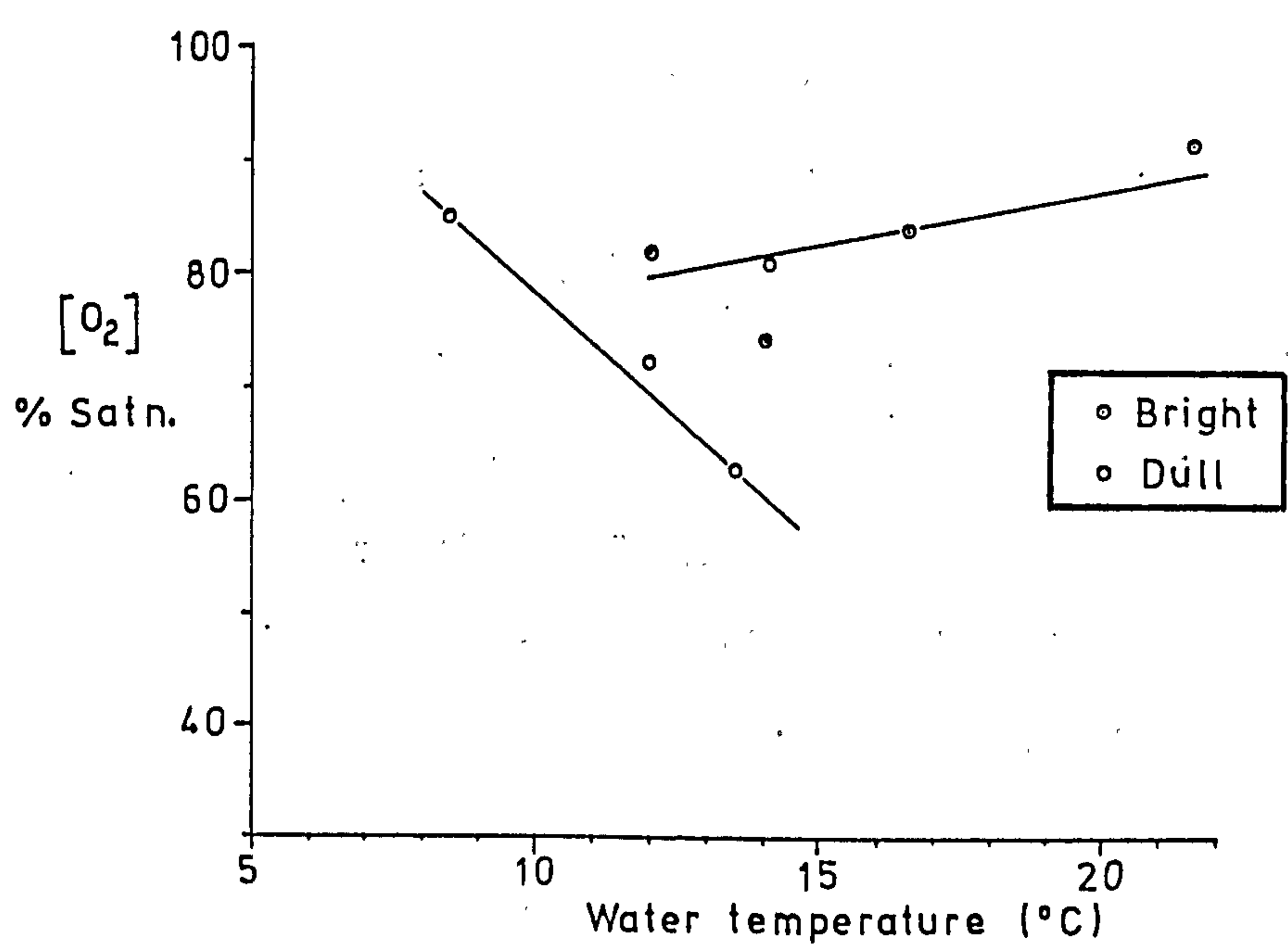
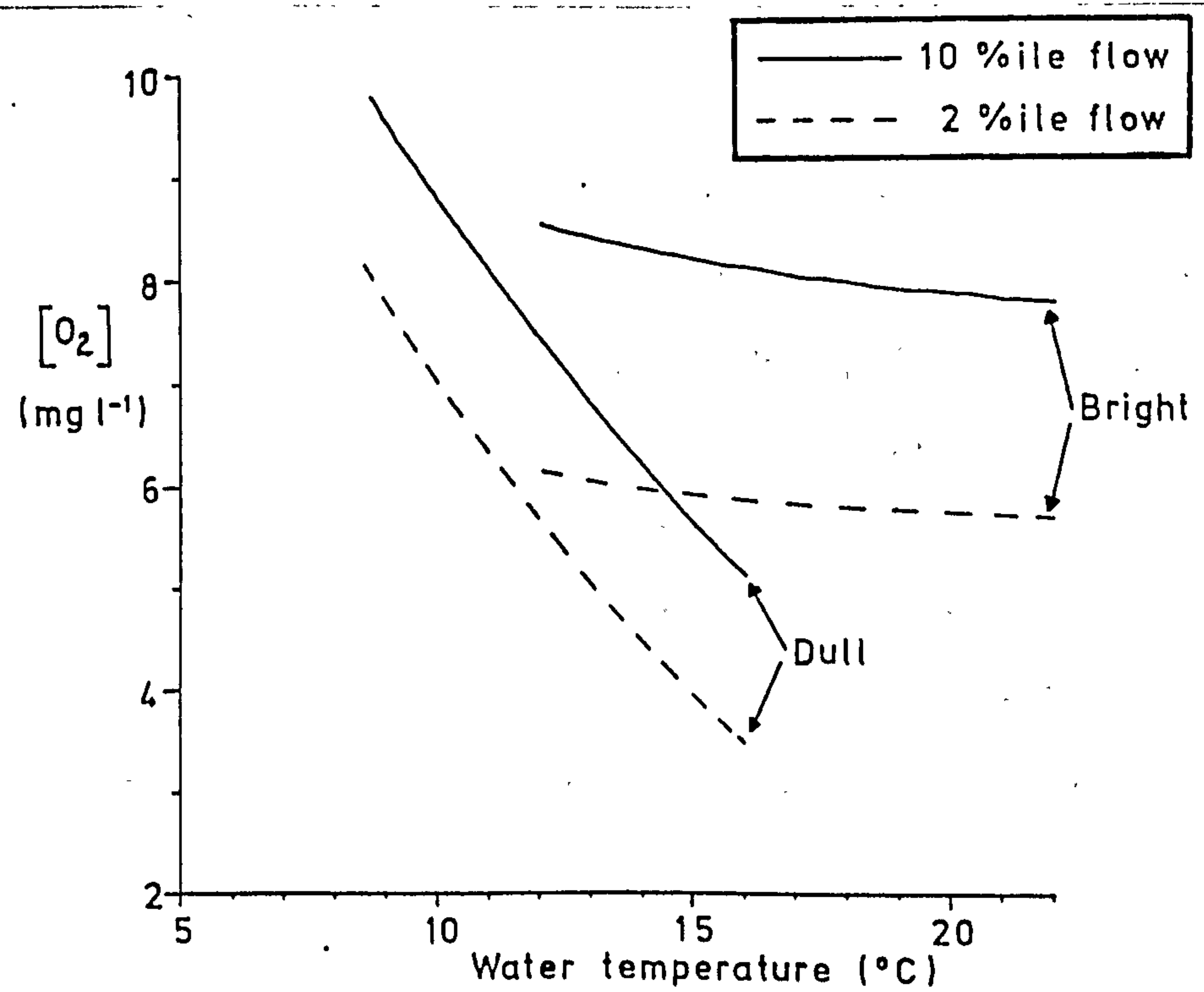


FIGURE 3.13 : The Relation Between Daytime D.O. and Water Temperature, for Both Dull and Bright Conditions, at the 2 and 10 Percentile Flow Levels at Cramond Bridge on the R. Almond





two-way index of "sunshine" was adopted, whereby the different measurements were considered to have been made in (i) "bright conditions" if more than 1 hour of bright sunshine, occurred at Turnhouse on the relevant day, prior to the water sample being taken, and (ii) "dull conditions" if less than 1 hour of bright sunshine was similarly recorded. This is a very crude index, as among other things, it is extremely inflexible, it includes no consideration of the distribution or timing of bright sunshine, and the data used correspond to a different location, albeit ~~it~~ only 2 km distant.

When this distinction in brightness is made, more sense is made of the plotted values, as is shown by the two estimated lines of relation for "dull" and "bright" conditions on Fig. 3.12. The two points which deviate most from these lines can be explained by the fact that neither fits into the bright/dull categorisation very successfully. The point above the "dull" line involved a bright sunshine hours total of 0.4, whereas for the points on the line, this was zero. In the instance where the % saturation of D.O. is considerably lower than expected for the "bright" condition, this involved a bright sunshine hours total of 1.2, only just above the required minimum of 1.0. Thus, it can justifiably be assumed that in such conditions, D.O. levels would be less than those for "brighter" days.

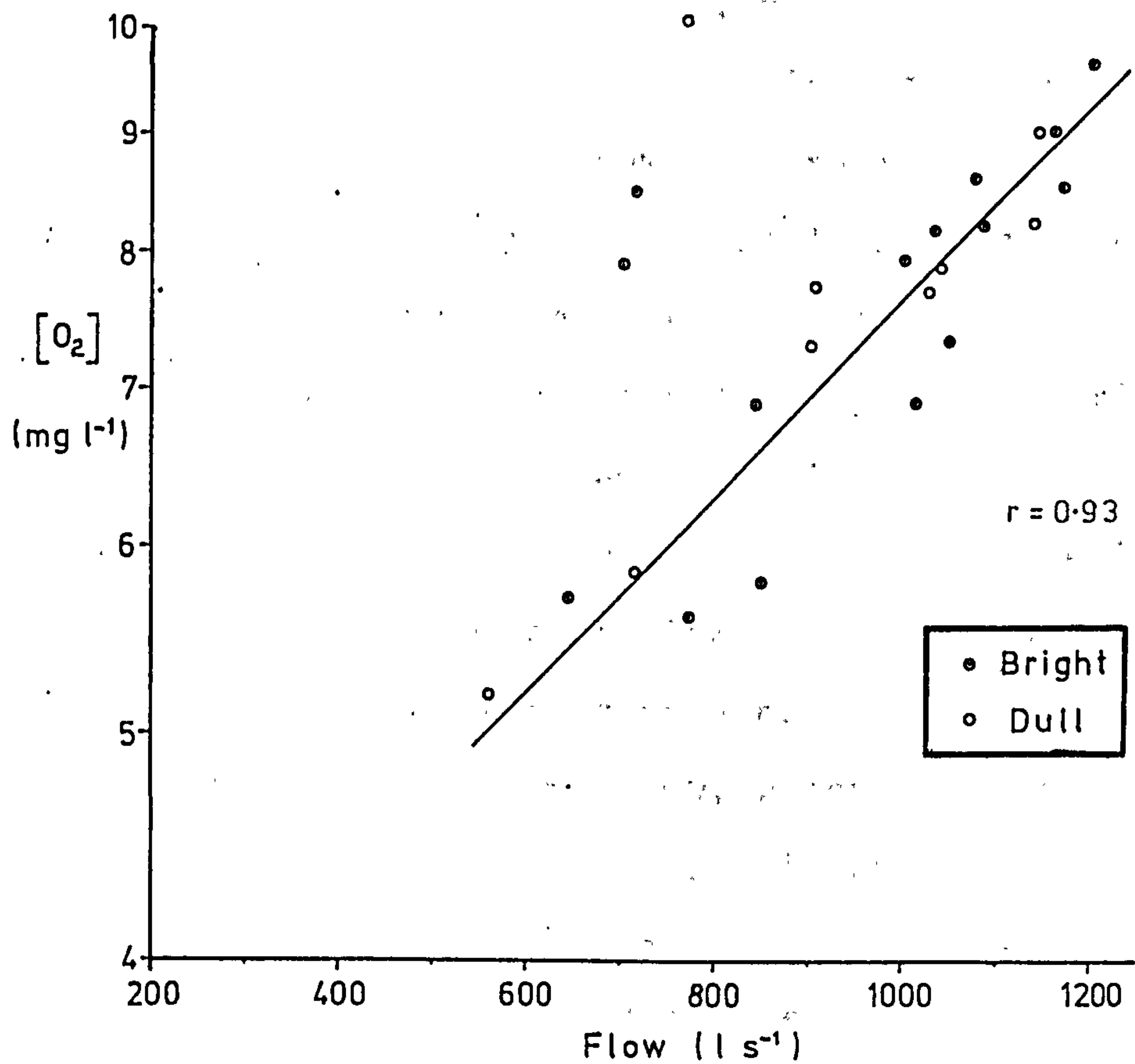
Using the plotted position of these relationships for flows around the 10 percentile level as a guide, other lines corresponding to eg. 5 and 2 percentile flows, for

which only a few plotting positions are available can be estimated. The curves of relation for "dull" and "bright" conditions corresponding to a flow at the 2 percentile level are shown alongside those for the 10 percentile flow in Fig. 3.13. On this graph, the vertical scale has returned to represent D.O. in terms of  $\text{mg l}^{-1}$ .

#### 3.3.5.4 The Combination of Flow, Temperature and Sunshine in the D.O. Model

The calculated distinctive effects of water temperature and sunshine can now be applied to the flow/D.O. relationship. Firstly, the effect of incorporating these features in improving the original D.O. model should be assessed. This was done by using curves such as those in Fig. 3.13 to adjust the 24 low flow D.O. values to those for standardised conditions of water temperature and sunshine. The chosen reference conditions were those corresponding to the median water temperature of  $16^{\circ}\text{C}$  in the "bright" category of the sunshine index. The correlation coefficient of the adjusted distribution, shown in Fig. 3.14, is 0.93. Hence, the variations in flow, water temperature and the sunshine index can be shown to account for 86% of the variation in D.O. concentration. All but 3 of the 24 points adjusted to median water temperature are close to the adopted line of relation. The deviations in these cases are somewhat extreme and therefore merit some attempt at explanation.

**FIGURE 3.14 : The Relation Between Low Flows and Daytime D.O. Levels (Adjusted to Correspond to the Median Low Flow Water Temperature in Bright Conditions of 16°C) at Cramond Bridge on the R. Almond**

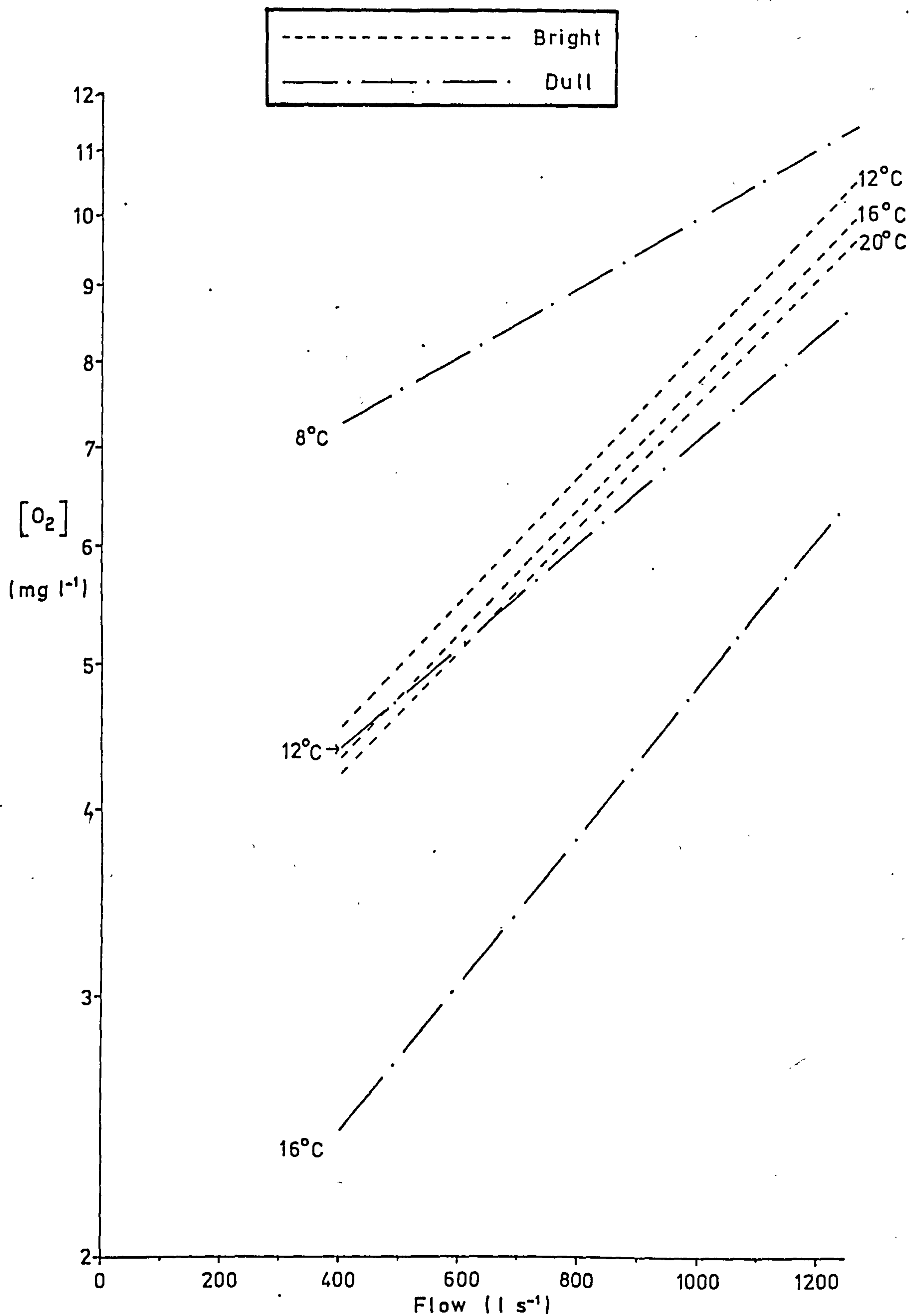




The sample registering an adjusted D.O. of  $8.5 \text{ mg l}^{-1}$  was taken on 7.7.71. This date coincides with the annual summer holidays in the Lothian Region, and since levels of  $\text{NH}_4$  and  $\text{NO}_3$  were inordinately low for the same sample ( $0.8$  and  $1.9 \text{ mg l}^{-1}$  respectively), it seems reasonable to assume that this unexpectedly high D.O. value could be due to a reduced sewage effluent load in the river. A specific explanation for the remaining two instances of surprisingly high D.O. is harder to find. The possible causes are numerous. For example, a variation in the output of a sewage works, the taking of an unrepresentative sample, errors in chemical analysis and a shortcoming of the adopted predictive model could all contribute to these discrepancies. On the first point above, enquiries made to the relevant authority as to variations in quality and quantity of sewage effluent received no reply. Since remaining sources of error or variation are largely unquantifiable, then the variation in D.O. values obtained for the two remaining samples remains unexplained.

The combined effects of flow, water temperature and sunshine (as measured by the simple index), on the D.O. concentration at Cramond Bridge are illustrated on Fig. 3.15. In this diagram, the ranges of D.O. for both "dull" and "bright" conditions are shown by lines representing the median water temperatures (of  $12^\circ\text{C}$  and  $16^\circ\text{C}$  respectively), and others involving a  $\pm 4^\circ\text{C}$  deviation from them. This is the maximum recorded deviation for each circumstance in low flow conditions, except for higher temperatures in

**FIGURE 3.15 : A Predictive Model for Daytime D.O. at Cramond Bridge on the R. Almond, Illustrating the Effects of Flow, Water Temperature and the Brightness Index**



bright conditions which have been recorded at  $6^{\circ}\text{C}$  above the median value of  $16^{\circ}\text{C}$ .

As is apparent, the  $\pm 4^{\circ}\text{C}$  range of possible water temperatures in "dull" conditions is associated with a much greater variation in D.O., than for "bright" conditions. Whereas, in the more sunny situation, D.O. concentration can reasonably precisely be derived from flow alone, in the "dull" situation, water temperature appears to be a very influential factor for the determination of D.O. levels. For example, in both sets of conditions at median low flow water temperatures, a drop of  $450 \text{ l s}^{-1}$  from a flow of  $1,000 \text{ l s}^{-1}$  is associated with a reduction in D.O. from above  $7 \text{ mg l}^{-1}$  to below  $5 \text{ mg l}^{-1}$ . At the same original flow, a similar drop in D.O. can be achieved in "dull" conditions by a water temperature increase of  $4^{\circ}\text{C}$ , whereas with the same temperature increase in "bright" conditions the D.O. still remains above  $7 \text{ mg l}^{-1}$ .

Thus, the other main detrimental influence on D.O., apart from low flows would seem to be dull and warm weather.

#### 3.3.5.5 A Consideration of Explanations for the Behaviour of the D.O. Model

The adopted procedure for predicting D.O. levels in low flow conditions could not be confidently applied without some consideration of its rather empirical nature, in relation to actual processes involved.

The direct effect of reduced flow levels can be considered as twofold. Firstly, there is a decreased amount of



water available for the dilution of oxygen-deprived sewage effluents. Secondly, and perhaps less importantly, the lower velocity and turbulence of flow could result in a decreased aeration of river water. A further physical effect, as mentioned previously is that higher water temperatures reduce the solubility of oxygen in water. For example, the maximum solubility of  $10.8 \text{ mg l}^{-1}$  at  $12^{\circ}\text{C}$  drops by 8.4%, to  $9.9 \text{ mg l}^{-1}$ , with a temperature increase to  $16^{\circ}\text{C}$ .

Other major influences on D.O. will be those associated with biological activity in the R. Almond. At Crammond Bridge, this can largely be linked to the behaviour of algae, as stated previously. Consideration of the respirational and photosynthetic behaviour of the algae and other organisms present, can reveal credible reasons for the measured indirect effects of water temperature and "brightness". A reduction in D.O. arising from increased respiration rates can be associated with higher water temperatures, whereas an increase in D.O. due to greater rates of photosynthesis can be linked with "brightness". Thus, at higher temperatures, in dull conditions it is most probable that D.O. levels are significantly reduced by higher respiration rates. Similarly, this effect could be expected in brighter conditions, however it appears to be very much offset by increased rates of photosynthetic oxygen production.

### 3.3.6 Application of the Predictive Models of Water Quality Parameters to the 1971-76 Period

#### 3.3.6.1 Standards of Acceptable Water Quality

In this section, the estimated levels of the various water quality parameters occurring during the period 1971-76 are considered, in relation to long term values and also some recommended acceptable limits of concentration. As regards the adoption of such acceptable standards, or what could alternatively be viewed as "demands" made on a water resource, much work has been published. For example Wuhrmann and Woker (1955), Doudoroff and Shumway (1967) and the European Inland Fisheries Advisory Commission (1973) all comment on desirable and critical levels of D.O. for various species of fish. However, few publications have attempted to set acceptable standards for river pollution in relation to the requirements of aquatic life. One exception is that of the Commission of the European Communities (C.E.C.) of 1973. This document recommends percentile limits for several water quality parameters, designed to allow fish to live in "favourable conditions". Separate standards are suggested for cyprinid and salmonid waters, the latter being defined as "waters which support or are capable of supporting fish belonging to species such as salmon, trout and grayling". Furthermore, in some cases, two classes of values (to be denoted (1) and (2) ) for each of the two types of water above are put forward.

The percentile levels of incidence of the various measures of water quality estimated for the R. Almond at Cramond Bridge are compared with some or all of these standards. Although it is considered that the location under concern should be treated at least potentially as a "salmonid water", albeit of a 2<sup>nd</sup> rather than 1<sup>st</sup> class nature, the situation is complicated by the seasonal variation of water quality requirements, associated with the behaviour of migratory fish.

#### 3.3.6.2 Water Quality During the 1971-76 Period

Three different methods of estimating the condition of the water in the R. Almond at Cramond Bridge are used, depending on the success and type of the various predictive models developed previously.

The first method refers to the concentrations of  $\text{NO}_3$  and  $\text{NH}_4$ , for which no satisfactory predictive relationship was found. Therefore, estimates of the distribution of the levels of these parameters have to rely directly on the 90 samples taken over the 1971-76 period. Fortunately, the distribution of these 90 sample flows very closely matches that of all of the daily mean flows over the 6-year period, thus removing any possibility of bias related to flow in the case of  $\text{NH}_4$  concentration. Accordingly, the distribution of sampled  $\text{NH}_4$  and  $\text{NO}_3$  values are taken to represent the conditions over the whole six years.



The water quality conditions for the 1971-76 period are now compared with those corresponding to the long term (1961-78) flow conditions, and relevant C.E.C. standards, for each of the parameters considered.

### NO<sub>3</sub>

The lack of a definitive relationship between flow and [NO<sub>3</sub>] (see Fig. 3.7) means that the distribution of [NO<sub>3</sub>] values over the 1971-76 period probably closely resembles that of the long term (1961-78) situation, and thus the two cannot be meaningfully separated.

TABLE 3.3 : Nitrate Levels for 1971-76 and the Long Term

[NO <sub>3</sub> ] mg l <sup>-1</sup>	% of time ≥ stated concentration		
	1971 - 76	Long term	C.E.C. Standard
3	75	(75)	10 for salmonids
6	3	(3)	10 for cyprinids
9	-		

Comparison with C.E.C. standards reveals that although conditions overall meet those advised for cyprinid waters, the incidence of NO<sub>3</sub> concentrations exceeding or

equalling  $3 \text{ mg l}^{-1}$  is 7.5 times that recommended for salmonid waters (see Table 3.3 ).

$\text{NH}_4$

Once again, the occurrence of given levels of this parameter are very similar over the period 1971-76 and the long term, as shown in Table 3.4.

TABLE 3.4 : Ammonia Levels for 1971-76 and the Long Term

$[\text{NH}_4]$ $\text{mg l}^{-1}$	% time $\geq$ stated concentration		
	1971 - 76	Long term	C.E.C. Standard
1	47	40	5 for salmons (2)
2	15	12	
3	1	0	

Consequently, whereas the rate of incidence of concentrations greater than or equal to  $1 \text{ mg l}^{-1}$  is 47% and 40% of the time over the 1971-76 and long term periods respectively, both represent a much greater level of occurrence than the relevant C.E.C. standard of 5%. Indeed, the 5% exceedence concentration for the 6-year period is

2.6 mg l<sup>-1</sup>, which is considerably higher than the C.E.C. level of 1 mg l<sup>-1</sup>.

The second method of estimating the distribution of conditions over the relevant periods applies to both NO<sub>2</sub> and PO<sub>4</sub> concentrations. In both cases, the relationships between these parameters and that of flow (see Figs. 3.8 and 3.6) can be used in conjunction with percentile flow data to estimate the incidence of given levels of pollution.

#### NO<sub>2</sub>

Considering firstly the differences between the 1971-76 and long term situations, as shown in Table 3.5, the following observation is of most importance. That is, that only at the higher concentrations of NO<sub>2</sub> did the increased incidence in 1971-76, compared to the long term, reach notable levels. Indeed, the greatest factor of increased occurrence took place at concentrations equalling or exceeding 0.7 mg l<sup>-1</sup>. It would appear that these levels were 2.5 times more prevalent during 1971-76 than they would normally be.

As regards C.E.C. standards, that for salmonid waters is grossly exceeded for both time periods. However, whereas normally the standard for cyprinids would be almost met, the limiting concentration was nearly twice as often exceeded during the 1971-76 period, than over the long term normal situation.



TABLE 3.5 : Nitrite Levels for 1971-76 and the Long Term

[NO <sub>2</sub> ] mg l <sup>-1</sup>	% of time ≥ stated concentration		
	1971 - 76	Long term	C.E.C. Standard
0.05	90	83	10 for salmonids
0.1	74	67	
0.3	40	29	
0.5	19	11	10 for cyprinids
0.7	11	44	
0.9	2.7	1.3	

PO<sub>4</sub>

The initial comments concerning NO<sub>2</sub> concentrations apply also to those of PO<sub>4</sub>. With this parameter, the highest increased factor of incidence during the 1971-76 period occurred at concentrations equalling or exceeding 1.6 mg l<sup>-1</sup>, which were similarly 2.5 times more prevalent than over the simulated long term situation.

TABLE 3.6 : Phosphate Levels for 1971-76 and the Long Term

[PO <sub>4</sub> ] mg l <sup>-1</sup>	% of time ≥ stated concentration		
	1971-76	Long term	C.E.C. Standard
0.2	71	64	10 for salmonids
0.4	54	43	10 for cyprinids
0.8	31	20	
1.6	10	4	

Once again, the 10% exceedence concentrations are of vastly different proportions as Table 3.6 shows, eg. 0.2 mg l<sup>-1</sup> for the C.E.C. standard for salmonid waters, against 1.6 mg l<sup>-1</sup> for the period 1971-76. Indeed, neither of the two recommended standards are anywhere near actual levels of occurrence; so much so that the influence of the 6-year low flow period involves only a relatively small degree of increased incidence, compared with that of the long term normal, at the relevant PO<sub>4</sub> concentrations.

#### D.O.

The complexity of the foregoing predictive model for D.O. concentration requires a more involved procedure. However, a day to day estimation of typical daytime D.O. status (at 12 noon) can be achieved<sup>ie</sup> by consideration of the 3 relevant factors, as follows;

- (i) daily mean flow;

(ii) the number of hours of bright sunshine prior to noon;

(iii) water temperature.

By use of all three variables, a series of daily estimates of D.O. concentration can be derived using relationships such as those shown on Fig. 3.15. The percentage exceedence values for given levels of D.O. are summarised for the periods of interest in Table 3.7.

TABLE 3.7 : D.O. Levels for 1971-76 and the Long Term

D.O. mg l <sup>-1</sup>	% of time $\geq$ stated concentration		
	1971-76	Long term	C.E.C. Standard
5	2.4	0.8	0 for salmonids (2)
7	13.4	6.5	5 "
9	32.2	19.1	50 "

Of the long term exceedence values, that at 9 mg l<sup>-1</sup> of D.O. comfortably satisfies the C.E.C. standard, and the other two at lower D.O. levels coincide closely with the relevant standards. Thus, the C.E.C. values shown in Table 3.7 seem particularly applicable in this case.

Comparison of the 1971-76 and simulated long term situations illustrates the increased incidence over the former period at all low D.O. levels, the factor of increase being higher at lower concentrations. For example, for



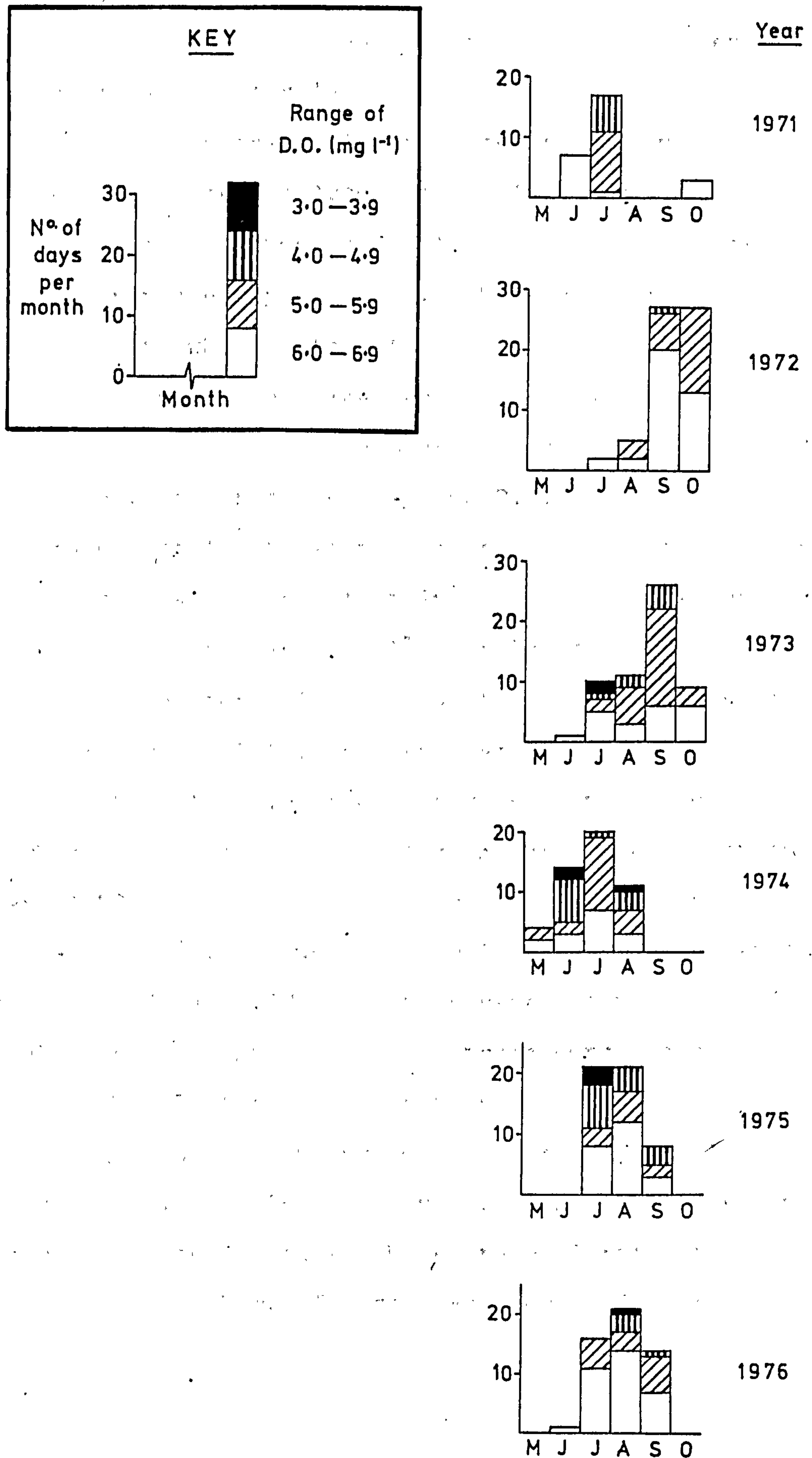
D.O.'s of less than or equal to  $5 \text{ mg l}^{-1}$ , which are not at all acceptable in the C.E.C. standard, there is an increased frequency of occurrence of threefold in the 1971-76 period compared to the long term. The possible environmental impacts of such deteriorations in water quality are now considered, with specific regard to the seasonal requirements of the R. Almond fishery.

### 3.3.6.3 The Seasonal Nature of Water Quality Deterioration And Possible Environmental Impacts During the 1971-76 Period

Fig. 3.16 illustrates the frequencies of occurrence of categorised D.O. values for individual years, on a monthly basis. It is considered that this time unit is adequate for a seasonal analysis, since, for example, an investigation of the number of consecutive days with D.O. levels less than given limits, would be rendered somewhat redundant by the rather extreme levels of diurnal variation indicated earlier.

The occurrence of typical daytime D.O. concentrations less than  $7 \text{ mg l}^{-1}$  was seemingly restricted to the months from May to October inclusive, during the 1971-76 period. As Fig. 3.16 shows, the lowest predicted D.O. levels, ie. less than  $4 \text{ mg l}^{-1}$ , are somewhat rare, and were restricted to the months of June, July and August. The major influences are the relatively high water temperatures and dull conditions which were prevalent in such instances. The flow levels in such periods, typically in the range  $500-600 \text{ l s}^{-1}$  were the same as those experienced over the latter half of

**FIGURE 3.16 : The Predicted Incidence of Low Daytime D.O. Levels at Cramond on the R. Almond in Individual Months During the Years 1971 to 1976**



October 1972. However, the lower temperatures (around  $10^{\circ}\text{C}$ ) at that time of the year result in predicted D.O. levels which are always greater than  $5\text{ mg l}^{-1}$ .

As regards the seasonal requirements of migratory fish, the Almond Angling Association (1980) has stated that the main runs of sea-trout and a few salmon occur between mid-September and early November. Therefore, in the years 1974, 75 and 76, when in fact the severest daytime D.O. levels seem to have been experienced, this would in all probability not affect the passage of migratory fish. After mid-September, the predicted daytime D.O. levels are all greater than  $7\text{ mg l}^{-1}$  in each of these three years. However, in 1972, and to a lesser extent in 1973, calculated daytime D.O. levels of less than  $7\text{ mg l}^{-1}$  persist for most of September and October. In November 1972, water temperatures were so low (around  $7^{\circ}\text{C}$ ), that even at flow levels of  $700\text{--}800\text{ l s}^{-1}$ , the predicted D.O. concentrations remain above  $7\text{ mg l}^{-1}$ . Although all but a few days of the months of September and October, 1972 have predicted daytime D.O. levels in the range  $5 - 7\text{ mg l}^{-1}$ , it must be questioned as to whether this in itself would have affected the passage of migratory fish, especially in the light of other extreme conditions of low flow and high pollutant concentrations.

For illustration, the hydrograph for the year 1972 is shown in Fig. 3.17. Since  $\text{PO}_4$  and  $\text{NO}_2$  concentrations can be directly related to flow, these are calibrated on scales alongside that of flow. The relevant period from mid-September

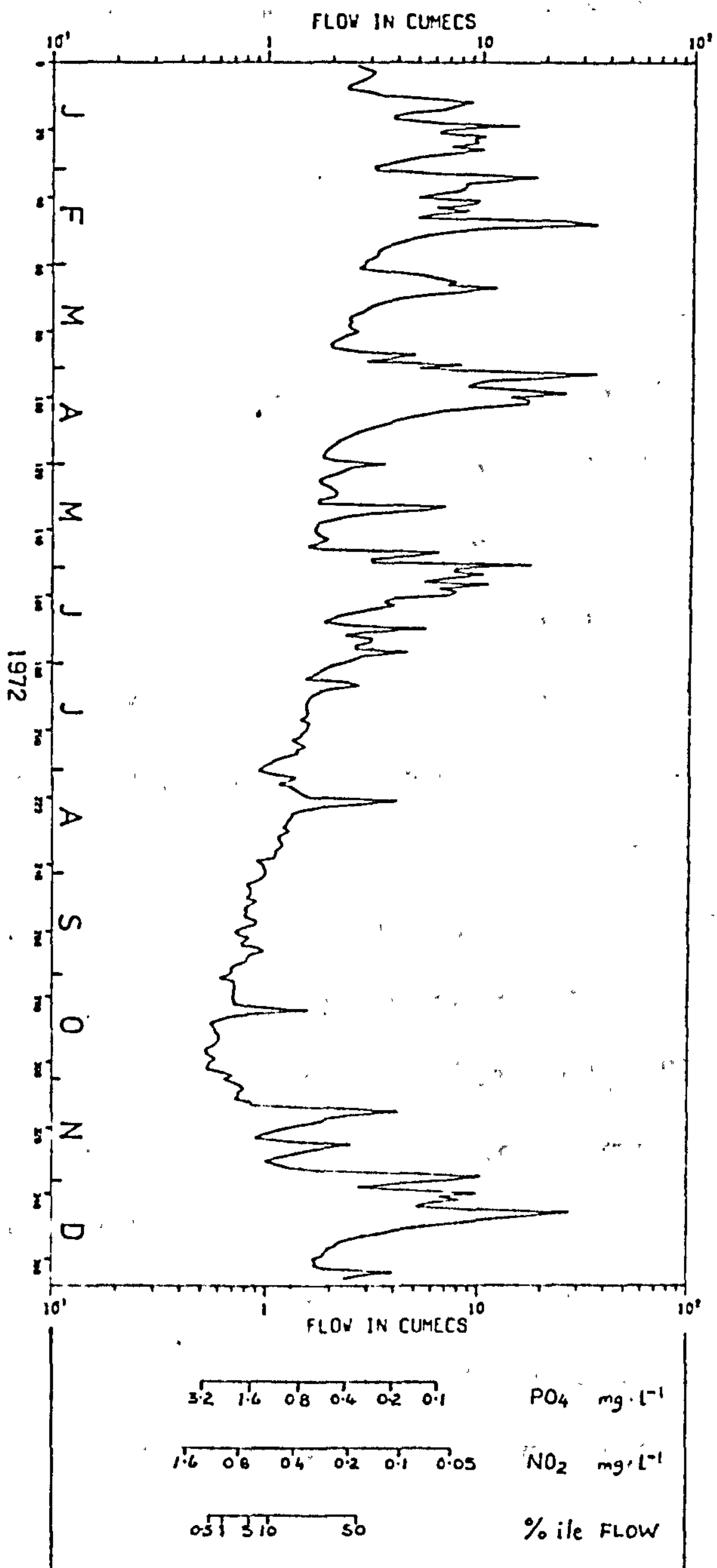


to early November 1972, can be seen to encompass the most adverse conditions for migratory fish as regards flow and  $\text{PO}_4$  and  $\text{NO}_2$  concentrations. For example, (i) the flow was less than the 5 percentile level ( $860 \text{ l s}^{-1}$ ) which corresponds to  $\text{PO}_4 = 1.6 \text{ mg l}^{-1}$  and  $\text{NO}_2 = 0.7 \text{ mg l}^{-1}$  for all but a few days, and (ii) the flow remained below the 1 percentile level ( $640 \text{ l s}^{-1}$ ), and hence predicted  $\text{PO}_4$  above  $2.3 \text{ mg l}^{-1}$  and  $\text{NO}_2$  above  $1.0 \text{ mg l}^{-1}$ , for 17 consecutive days in October.

Unfortunately, it has not been possible to produce a reliable predictive model for  $\text{NO}_3$  and  $\text{NH}_4$  levels. The lack of estimates for nitrate and ammonia concentrations, coupled with the lack of specific details of the requirements of resident and migratory fish populations means that no firm conclusions can be reached as to the direct and indirect environmental impacts associated with the low flows of the 1970's on the lowest reaches of the R. Almond. However, some tentative conclusions based on generalised C.E.C. requirements for inland fisheries (shown in Tables 3.3 to 3.7) can be put forward.

As regards the effects of reduced levels of water quality on resident fish populations, no unusually large scale fatalities were reported (Forth River Purification Board, 1971-76). In view of the extreme levels of diurnal D.O. variation that can occur in summer at Cramond Bridge, it is most likely that "resident" salmonid populations move temporarily to more favourable upstream stretches in such conditions. Therefore, severe daytime water quality

**FIGURE 3.17 : Hydrograph of Daily Mean Flows and Predicted Pollutant Levels at Crawford Bridge on the R. Almond During the Year 1972**



conditions may not be particularly relevant in these circumstances. Even for truly resident species, the day-time D.O. levels, severe as they would appear to have been during the 1971-76 period, could not be considered to be limiting factors compared to maximum overnight D.O. summer season depletions.

In relation to the effects of reduced water quality levels on migratory fish, no information as to actual fish catches is available (Almond Angling Association, 1980). However, judging by the C.E.C. standards (shown in Tables 3.3 to 3.7), it would seem to be the case that all five water quality parameters measured at Cramond Bridge would have presented an obstruction to the seasonal upstream passage of such species during the 1971-76 period, particularly in 1972. Which of these parameters could be considered as the most limiting factor is not known. In general terms however, the most severe increased pollution levels, ie. those of 1972, could be considered to have at best delayed, and at worst prevented the passage of migratory fish.

Perhaps in a situation where there were more direct human interests, such as economic ones, more information would be available for the assessment of drought impacts. This consideration applies to the second part of Section 3, that concerning the impact of the 1971-76 drought on public water supply requirements.



### 3.4 DROUGHT IMPACTS ON WATER SUPPLY SYSTEMS

#### 3.4.1 Water Supply in the East of Scotland

Before any investigation of drought impacts on water supply systems, it is useful to make some assessment of the water resources which had been developed and were being utilised in the early 1970's. Fortunately, in 1971, just prior to the commencement of the drought period, the Scottish Development Department (S.D.D.) had carried out a general survey of water resources in Scotland. The following details for individual water authority areas concerning eg., population, water consumption and yields and types of source are all taken from this document, published in 1973.

Shortly after this, under the local government reorganisation of 1975, the administrative responsibility of public water supplies in Scotland was transferred to the newly-created regional authorities, whose areas are indicated in Appendix 1. The following information is based on the foregoing regional water boards, in existence from 1968 to 1975, which are also shown in Appendix 1. This is probably more appropriate, since this interval includes the longest and severest parts of the drought period. Only those water boards serving at least in part those areas which have been previously identified as suffering more severe meteorological and hydrological events, ie. eastern Scotland, are included.

For each Water Board area in this part of the country, Appendix 8 summar<sup>s</sup><sub>ies</sub> the relevant population and water consumption statistics. The most notable features are firstly, the very small proportion of private water supplies in use in central and southern areas (typically less than 1% of the total supply) compared with values of around 10% in the more sparsely populated northern regions. Nationally, public water supplies serve 98.2% of all domestic consumers (1971 S.D.D. figure). A second major point of interest concerns the remarkably similar levels of total consumption per head of population, all but two regional averages being in the range 320-380 l hd<sup>-1</sup> d<sup>-1</sup>.

In addition, regional proportions of domestic and trade consumption do not vary much from the 1971 national average of 65% and 35% respectively, except perhaps in northern areas. The only exception to these two general trends is the former Mid-Scotland Water Board area, by virtue of the provision of large water supplies to industries in Grangemouth.

#### 3.4.2 Type and Location of Water Supply Sources in The East of Scotland.

As Fig. 3.18 illustrates, in 7 of the 8 water board areas at least partly in the East of Scotland, impounding reservoirs and lochs contribute over 70% of the total supply capability. The one exception is the North East of Scotland Water Board area, where this contribution is only

15% of the total. In general terms, the central areas are most dependent on reservoired sources, eg. there is a 98% dependence for the Mid-Scotland Water Board area. Rather surprisingly, this value also applies to the North of Scotland area, however this preference for reservoired supplies may be a response to the extremely low flow levels encountered in this part of the country. Figs. F. 1 and F.2 (located in the rear cover folder) indicate the widespread occurrence of 1 and 5 percentile flows of less than  $1 \text{ l s}^{-1} \text{ km}^{-2}$  in this area. Individual yields as low as one-tenth of this figure have been recorded (Highland Regional Council, Dept. of Water and Sewage, 1978).

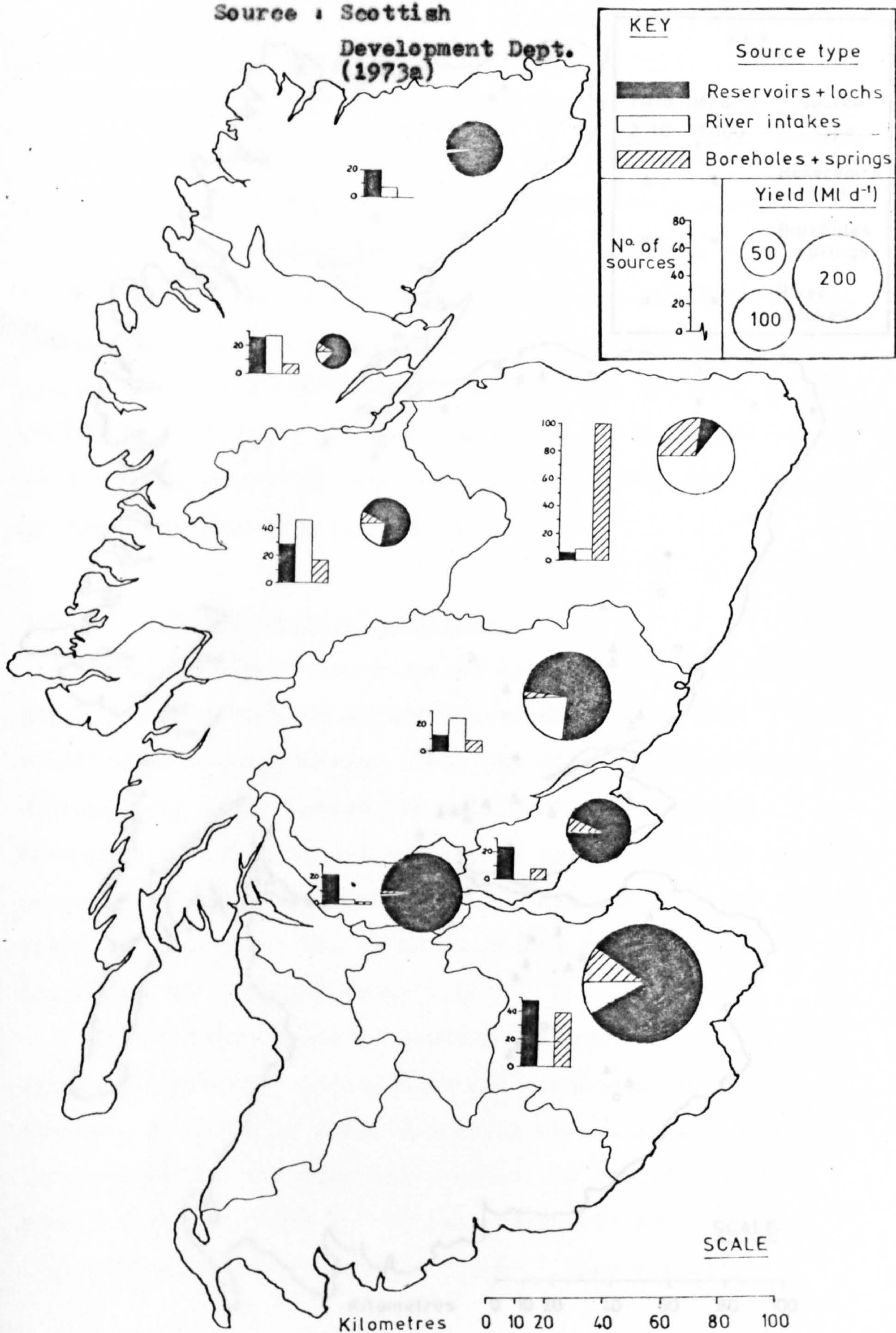
Comparison of the proportion of water supply yields attributable to the three different categories of source type, and the number in each category, as shown in Fig. 3.18, can give an indication of the size of yields from individual sources. Generally speaking, in instances where a high proportion of supply is from reservoirs and lochs, the number of individual sources is small, and individual yields tend to be large. For example, Mid-Scotland's 28 sources are capable of supplying  $157 \text{ Ml d}^{-1}$ , whereas a similar total yield involves 115 sources (mostly comprising springs) in the North East of Scotland Water Board area. As a rule of thumb, yields from impounding reservoirs and lochs tend to be greater than those from river intakes, which in turn are usually larger than those from springs and boreholes.



**FIGURE 3.18 : The Numbers of, and Total Yields Available From, Different Source Types in the Individual Water Board Areas in the East of Scotland in 1971**

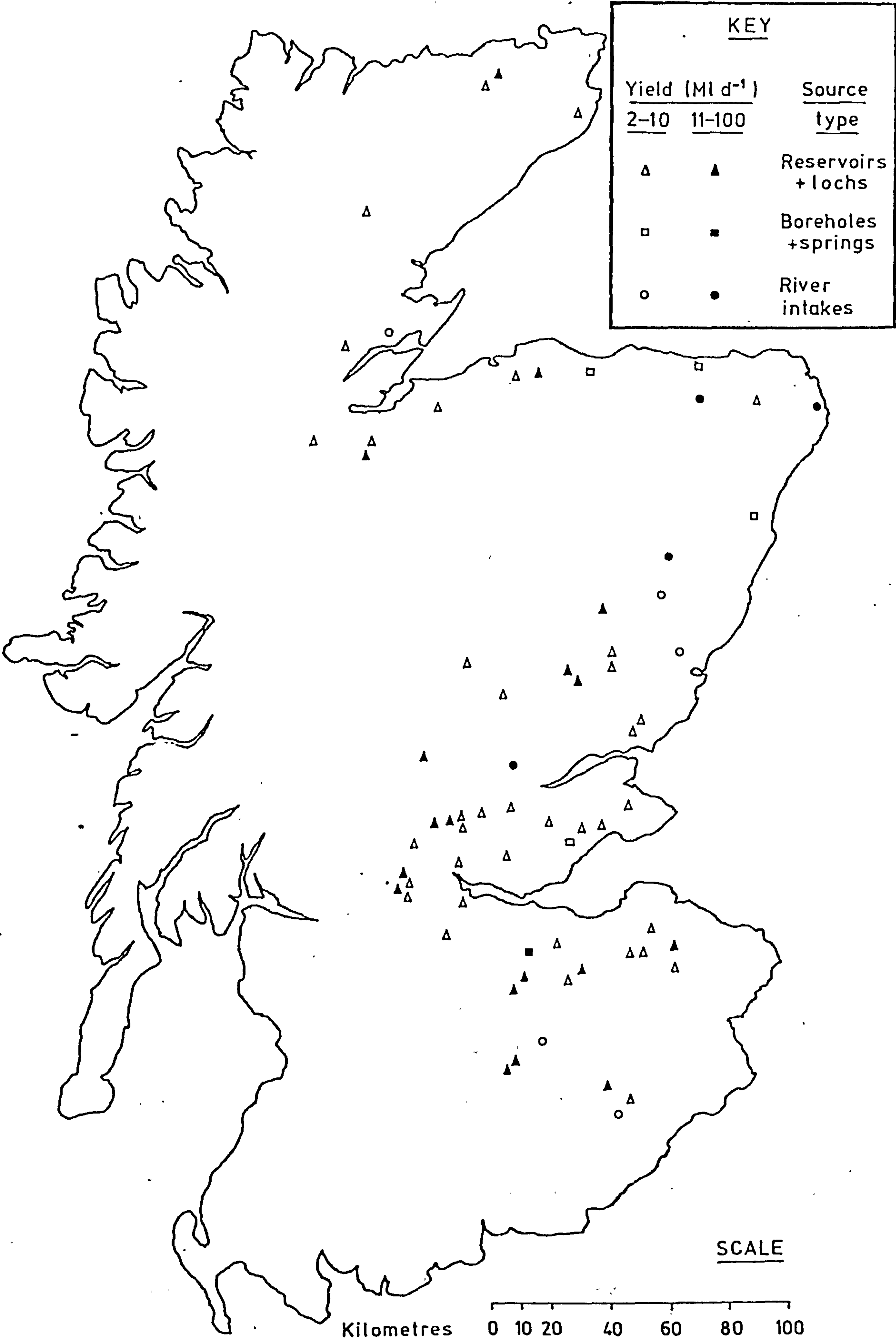
Source : Scottish

Development Dept.  
(1973a)





**FIGURE 3.19 : The Location, Type and Size of the Major Water Supply Sources in the East of Scotland in 1971**  
**Source : Scottish Development Department (1973a)**



All water resources capable of supplying at least 2 and 10  $\text{ML d}^{-1}$  are indicated on Fig. 3.19. These lower limits were chosen to eliminate the inclusion of too many small sources, yet at the same time to illustrate best the geographical distribution of the more important water supply sources serving eastern Scotland. The map illustrates further the very dominant role played by reservoirs and lochs in the provision of public water supplies in all areas, except the north-east. Over eastern Scotland as a whole, this category of supply accounts for only 37% of the total number of sources, but for 80% of those capable of supplying more than 2  $\text{ML d}^{-1}$ .

#### 3.4.2.1 Linking of Supply Systems

In 1971, almost all linkages between different water supply systems were on an intra-regional basis, and confined to central areas. Both the Fife and Kinross and Mid-Scotland Water Boards had well developed regional networks, allowing most locations to be supplied, at least partly, from more than one source. This was also the case within each of the three districts comprising the South East of Scotland Water Board.

In all other parts of eastern Scotland, discrete supply areas mostly depended on one particular source. However, a change in Water Board policy was apparent. In the north-east, for example, a scheme to distribute water over a wide area from a "regional resource" at Turiff on the R. Deveron was commenced in 1968. More recently, in



Tayside, sources with a surplus supply capacity have had their areas of possible supply extended to include several towns which suffered shortages and restrictions during the 1971-76 period.

#### 3.4.3 State of Water Supply Sources During the 1971-76 Period

It would be very informative to present details concerning the state of water supply sources during the years 1971-76. However, the applicability of such an analysis would be severely limited by lack of data compatibility between sources of both the same and different types. The difficulties associated with each of the three categories of supply source mentioned earlier are now discussed in turn.

If, firstly, one attempts to use reservoir levels and storage volumes to compare the effects of the meteorological and hydrological events described in Section 2, two major difficulties arise. These can be identified as follows;

(i) the discrepancies between actual consumption rates and what is considered to be the "reliable yield". The relationship between these two values varies widely from reservoir to reservoir (as is shown later). This introduces an element of incompatibility. For example, a reservoir may be at a critically low level not just because of a shortfall in inflow but also because of an inappropriately high abstraction rate. Consideration of this factor

prohibits valid comparisons between storage deficiencies in different sources.

(ii) the choice of which variable to use to measure "the state" of each reservoir. The two possible alternatives are, firstly, the proportion of the total capacity in store, and secondly, the number of days supply available. Neither is particularly appropriate if geographical comparisons are intended, because the depletion and refill characteristics of individual reservoirs vary greatly. For example, in cases which could be said to be "under reservoired", storage may be expected to stay near the maximum nearly all the time, even though this volume of water may only represent 2 or 3 months supply. Constrastingly, in a different situation, a reservoir which is normally full rather rarely may be facing a potential supply failure if only 2 to 3 months supply is available.

In the case of river abstractions, the matter is much more straightforward. For example, the degree or proportion to which available flows fall beneath the quantity required by, or allotted to public water consumption could be used to derive an index of the "state" of the supply source. However, for the major river intakes, shown on Fig. 3.19, river flows comfortably exceeded the volumes abstracted for public consumption during the 1971-76 period.

As regards the minor river abstractions, some of which did fail to varying extents in their public water supply function, no flow information is available. Consequently, any comparative analysis is rendered impossible.



This situation also applies to the supply category comprising the underground sources. Insufficient information describing the condition of springs and boreholes is available to allow any analysis.

In view of all these considerations, it would not serve any useful purpose to attempt a comparative survey of the state of water supply resources over the 1971-76 period. However, what can be compared are the impacts upon normal public water demands and requirements, which to a large extent reflect the state of water supply sources in given areas. Such an appraisal now follows.

#### 3.4.4 Impacts on Public Water Supply System Requirements During the 1971-76 Period

In this section, the drought management measures taken by the various water authorities during the 1971-76 period are categorised and analysed from what generally approximates to the consumer's viewpoint. In this way it is hoped to represent most accurately the levels at which demands on the public water supplies were not fulfilled. This procedure has the additional benefit of not requiring obvious discriminations between the three categories of water supply sources described earlier.

Since the actions taken are not to be classified according to the effort involved from the water authorities, at this point, it should be noted that the elaboration and expense of the measures adopted to combat water



shortages are not always directly related to the consumer impacts, in terms of both the quality and quantity of water consumed.

The ~~aff~~ormentioned reorganisation of responsibilities and boundaries in 1975 inevitably interrupted the continuum of water supply management and planning policies over the period 1971-76. Whilst some data are available for say, the pre-regionalisation period, this may not always be the case for the latter period and vice-versa. In addition, the type and accessibility of information kept by the various water authorities varies from one to the other. Hence the comparability of such data can sometimes be limited. Nevertheless, by filling any gaps in information by consultation of the relevant local and regional newspapers (as listed in the bibliography), it has been possible to compile a national picture of the consumer impacts, as regards public water supply, in the 1971-76 period.

The various measurable, and also the less quantifiable effects on the availability and use of water from public sources during the years 1971 to 76 are now discussed in terms relating to;

- (i) consumer water quantity;
- (ii) consumer water quality;
- (iii) environmental effects.

#### 3.4.4.1 Consumer Water Quantity

The various elements which can be included under this type of impact are now considered in order of increasing severity.

### (1) Hosepipe restrictions

The power to inhibit, or restrict temporarily, the use of hosepipes, under Section 59 of the Water (Scotland) Act of 1946, provides one of the few courses water authorities can take directly, to reduce consumption of public supplies. Such a restriction, under the terms of the above Act, allows water authorities to,

"prohibit or restrict the use, for the purpose of watering private gardens or washing private motor cars, of any water supplied by them through a hosepipe or similar apparatus".

These bans, in themselves, cannot be regarded as an effective means of reducing water consumption, as the quantities of water drawn through hosepipes are, in all probability, minimal. The limited importance in this respect is reflected in the size of the penalty for contravention, a maximum fine of £5. Despite this consideration, such restrictions do serve as a vehicle for communication with the public, and are typically accompanied by various levels of publicity geared at reducing water consumption.

Prior to the 1970's, the last time large parts of Scotland were affected by water restrictions was in 1959 in the south, and 1955 in the north. However, in the period 1971-76 hosepipe prohibitions were a common and widespread occurrence in eastern Scotland. Over this 6-year period, some parts of the Grampian and Fife regions were subject to such restrictions for a total of 30 months (over 40% of the time). The longest duration of any single hosepipe



ban was that of 15 months, straddling the years 1972-74, in Edinburgh and Midlothian.

Figs. 3.20.1 to 3.20.6 show the durations and areal extent of hosepipe restrictions imposed over mainland Scotland in each year of the 1971-76 period. Bans tended to be imposed on areas ranging in size from individual towns to entire water board areas prior to 1975. Whereas, after local government reorganisation, the prohibitions were usually applied over complete districts or regions. Thus, compatability of the entire series of maps in Fig. 3.20 may be slightly limited. Furthermore, it should be noted here that the distribution and durations of hosepipe restrictions, whilst representing an objective measure of reduced availability of water to the consumer, is not so objective as regards the assessment of the lack of water available for supply. For instance, different water authorities have different policies of implementation, and the applicability of such restrictions varies for different types of supply source.

In addition, there is the added complication that sources of public water, especially upland reservoirs, are not always situated close to the areas of supply. Therefore, locations of low supply do not always correspond to those of reduced availability (see Fig. 4.1 for clarification of the geographical distribution of the main sources and their corresponding areas of supply).

Despite these elements of subjectivity and variance, the same annual patterns as discussed in Section 2,



concerning rainfall and run-off over the 1971-76 period, are again apparent. That is, the confinement of the 1971 hosepipe bans mainly to the far north and the Grampian region. These areas were similarly affected in the following year, but so too were the areas around the Firth of Forth and the Firth of Tay. By 1973, the year of the longest and most widespread prohibitions, the far north experienced short duration hose bans. However, Fife, part of the Lothians, Berwickshire and eastern parts of the Grampian Region suffered up to 12 months of this year under such restrictions.

This movement of reduced water availability from north to south is still apparent in 1974, when the bans of the largest scale and duration were those enforced in Fife and Midlothian. Once again in 1975, and thus for the fifth consecutive year, Fife was affected by hosepipe restrictions. So too was the coastal part of Tayside and the northernmost parts of the Grampian Region. Generally though, this year involved the shortest and least widespread hosepipe bans of the 6 years in the relevant period. However, the northward movement of the occurrence of restrictions continued and spread in 1976, the most affected areas being the far north and the Grampian Region. However, all bans were of a duration of 3 months or less.

Although the distribution and scale of these water use restrictions resemble those of low rainfall and run-off over the same period, there are some important differences. Generally speaking, the occurrence of hosepipe bans is not

as widespread over the relevant areas as are the abnormal meteorological and hydrological events. For example, the southeast of Tayside, whilst receiving similar levels of deficient rainfall as neighbouring Fife over the 1971-76 period, suffered much less from water restrictions. Also, that part of the country where the persistence of low flows has been identified as most severe in 1972 and 73, ie. East Lothian, never once had any hosepipe restrictions implemented over the 1971-76 period. Explanations for such apparent anomalies are investigated later in Section 4.3.2.

Although a hosepipe prohibition would seem to be a relatively standardised statutory procedure, as it happened, it meant quite different things to different types of water consumer, in different parts of the country.

If firstly, the strength of enforcement is considered, whereas some water authorities relied on public adherence to regular newspaper advertising of hosepipe restrictions, others took stronger action. For example, in some areas eg. Arbroath, Tayside in 1973, evening "water patrols" were employed by the East of Scotland Water Board to detect any misuse of hosepipes. In other areas, claims made by individuals as to contraventions of the ban were investigated. However, it would seem that the water authorities relied on persuasion rather than recourse to legal action, because no evidence of the imposition of fines for contravention of hosepipe bans was found.



**FIGURE 3.20.1 : The Extent and Duration of Hosepipe Restrictions Imposed in Scotland During the Year 1971**





**FIGURE 3.20.2 : The Extent and Duration of Hosepipe Restriction  
Imposed in Scotland During the Year 1972**





**FIGURE 3.20.3 : The Extent and Duration of Hosepipe Restrictions Imposed in Scotland During the Year 1973**





**FIGURE 3.20.4 : The Extent and Duration of Hosepipe Restrictions Imposed in Scotland During the Year 1974**





**FIGURE 3.20.5 : The Extent and Duration of Hosepipe Restrictions Imposed in Scotland During the Year 1975**





**FIGURE 3.20.6 : The Extent and Duration of Hosepipe Restriction Imposed in Scotland During the Year 1976**





The second point to be raised here concerns the consumer sector of enforcement of such bans. In most instances, these restrictions were applied in adherence of the spirit and words of the 1946 Act, ie. to "private" water consumption. However, one water board, who request to remain anonymous, undertook inappropriately strong action, to the extent that they imposed such bans on fourteen golf clubs, bowling greens, tennis courts, eighteen commercial automatic car washes and Local Government Authority activities.

Under the terms of the 1946 Act, presumably "private" sports clubs could be included in a hosepipe ban, if golf courses, bowling greens and tennis courts could be interpreted to be "gardens". So too could the washing of private vehicles by a commercial interest if an automatic car wash fits the description of "a hosepipe or similar apparatus". Clearly, these two contentions are somewhat dubious. Apart from the fact that most parties involved complained to the water authority, consumer reaction varied, in that some golf clubs, for example, developed private sources of water from boreholes, whilst another, albeit two years after the original restriction had been imposed, challenged the powers of the water authority, and recommenced watering. As regards the bans on automatic car washes, the water authority relented, but only after two separate prohibitions had been imposed.

Concerning other areas in which this particular authority applied hosepipe restrictions, these have even



less in the way of supportive argument. For example, such bans "prevented" the use of hoses to wash refuse collection and food-carrying vehicles, until the Road Haulage Association indicated that such action was in breach of hygiene regulations.

## (2) Publicity and public relations

Publicity campaigns to reduce private household water consumption varied in type and intensity over the country during the 1971-76 period. However, the initial step in all such actions was to accompany notification of a hosepipe ban with either a newspaper advertisement or article appealing for a reduction in water consumption.

Most water authorities kept their public relations campaigns at this level, with regularly repeated press notices. However, others used more intensive publicity measures. In Fife, for example, the need to save water was displayed on roadside posters and on thousands of car stickers and lapel badges. Verbal reminders were given by loudspeaker vans, and by water inspectors who visited schools. Further exposure of the urgency to conserve water supplies in the Fife and Kinross Water Board area was provided by television advertisements. In 1971, this water board's expectancy of all the above measures was to reduce domestic water consumption by 25%.

A further method of ensuring near saturation exposure of water conservation campaigns is to deliver appeals and advice to every household. Such leaflets were used in

Edinburgh in 1959 and 1973, and in parts of Fife in 1974. A typical example, produced by the former South East of Scotland Water Board, in 1973, is shown in Appendix 9.

The approach of persuasion can be particularly useful where relatively large quantities of water are used by the industrial/commercial sector, over which water authorities have no direct mandatory powers to impose water restrictions. Where water boards considered that savings could be made in this area, representations were made, usually by letter, around the same time as the imposition of hosepipe prohibitions.

In rural parts of the country, eg. the majority of the Grampian Region, such appeals were mainly directed at bodies such as Fire Brigades and Whisky manufacturers. As an example, an appeal to owners of automatic car washes in part of the East of Scotland Water Board area met with considerable success. Of the four operations involved, all co-operated to some extent by eg. offering to recycle water and to reduce opening hours.

In the more industrial areas, in some cases all commercial and industrial consumers from hotels to electricity generating stations were directly requested by water authorities to reduce their consumption. The Fife and Kinross Water Board's request to all metered consumers in 1971 for a 30% saving was generally considered unreasonable, according to consumer's replies and reactions. However, one sphere in which such appeals were most successful was that of local government authorities. For instance,



by way of co-operation, water consumption was reduced in areas such as sewer flushing, street washing, public toilets and municipal swimming pools. One would expect that with the administrative reorganisation of 1975, opportunity for such co-operation would be increased.

(3) Domestic waste detection

This rather intensive procedure was carried out on a house to house basis in parts of Tayside in 1973. The towns involved, which were already subject to hose-pipe restrictions were Kirriemuir, Forfar, Arbroath, and Blairgowrie. Items such as W.C.'S, taps, cisterns, mains and services found to be faulty, were repaired.

Other non-household waste detection measures were undertaken by most authorities during the 1971-76 period. As well as increasing efforts to some degree to detect and repair burst mains and services, most water authorities encouraged the public to report leaks.

(4) Decreasing water pressure in mains

No specific incidences of this practice could be found, although some water authorities had this measure included in their contingency plans. Such action, under the Water (Scotland) Act of 1946 (Fourth Schedule) can require the permission of the Secretary of State for Scotland.



(5) Rationing temporal availability of water

No instances of water supplies being shut off for part of the day on a regular basis, occurred during the water shortages of 1971-76. However, some evidence suggests that such action was only narrowly avoided in some cases. For example, a notice placed in the Dundee Evening Telegraph (of 20.9.73) by the Fife and Kinross Water Board, urging a 30% drop in consumption, stated that;

"Unless water consumption is reduced immediately, it will be necessary to impose further restrictions including the shutting off of water supplies at certain times of the day".

Judging by similar comments, such rationing was a distinct possibility in parts of Lothian around the same time, and again in Fife in 1974.

The most recent example of this procedure being adopted in Scotland, occurred in 1959 in Edinburgh and Midlothian. On this occasion, the Secretary of State for Scotland granted an order under Schedule 4 of the 1946 Act, allowing water supplies to be disconnected between the hours of 7p.m. and 7a.m.

(6) Use of stand pipes

The only incidence of the use of stand pipes as an alternative to normal domestic supplies of running water in the 1970's, occurred as a practice run in Fife in 1974. This took place as the Fife and Kinross Water Board,

fearing an unprecedented depletion of their reservoired resources, and hence the necessity of strict water rationing, decided to use the public in a trial run of stand pipe equipment in small restricted areas.

(7) Carting of water supplies

Only in the rural parts of the Grampian and Highland Regions, where individual small sources of water supply failed, and alternative supplies were unavailable, was water transported by road to consumers. This occurred in the years 1971, 72 and 73, and to a lesser extent in 1976.

The maps in Appendix 10 indicate for each of these years, the number of months for which water was carted to individual towns and villages in the affected parts of the country. The longest period over which delivery of water supplies by tanker was necessary was the 8 month spell from September 1972 to April 1973 inclusive, in the north east of the Grampian Region. However, in the majority of cases in this region, carting of water took place typically between the inclusive months of September to December 1971, August to November 1972, September to November 1973 and July to August 1976.

Unfortunately, very little information is available concerning the quantities of water transported by road to consumers. What records there are, would indicate that rates of carting to individual places usually lay between

500 and 10,000 litres per day. Also, it would seem to be the case that much of the carting was done to augment existing supplies, and provide clean drinking water. For example, the town of Newmachar in the Grampian Region received only 5% of its normal consumption (approx.  $100,000 \text{ l d}^{-1}$ ) by tanker, when local supplies ran into difficulty in August and September 1972.

#### 3.4.4.2 Consumer Water Quality

The two types of impact on water quality experienced during the 1971 to 76 period were associated with firstly, low water, and thus high sediment levels, in supply reservoirs and rivers, and secondly, with changes of supply source when normal ones failed to fulfill their desired function. These are now discussed in turn.

Several water authorities received complaints from consumers concerning a deterioration of the quality of water supplied during the 1972-73 spell, particularly in relation to reservoired sources. For instance, towards the end of 1972, when Gladhouse Reservoir in Midlothian was around only 20% full, the South East of Scotland Water Board received several complaints concerning the discolouration of water supplied from this source. Records reveal that similar complaints were registered when Cameron Reservoir supplying St. Andrews in Fife was at a similar level. Around the same time, in November 1972 (when total reservoired supplies were at one-third of maximum storage),



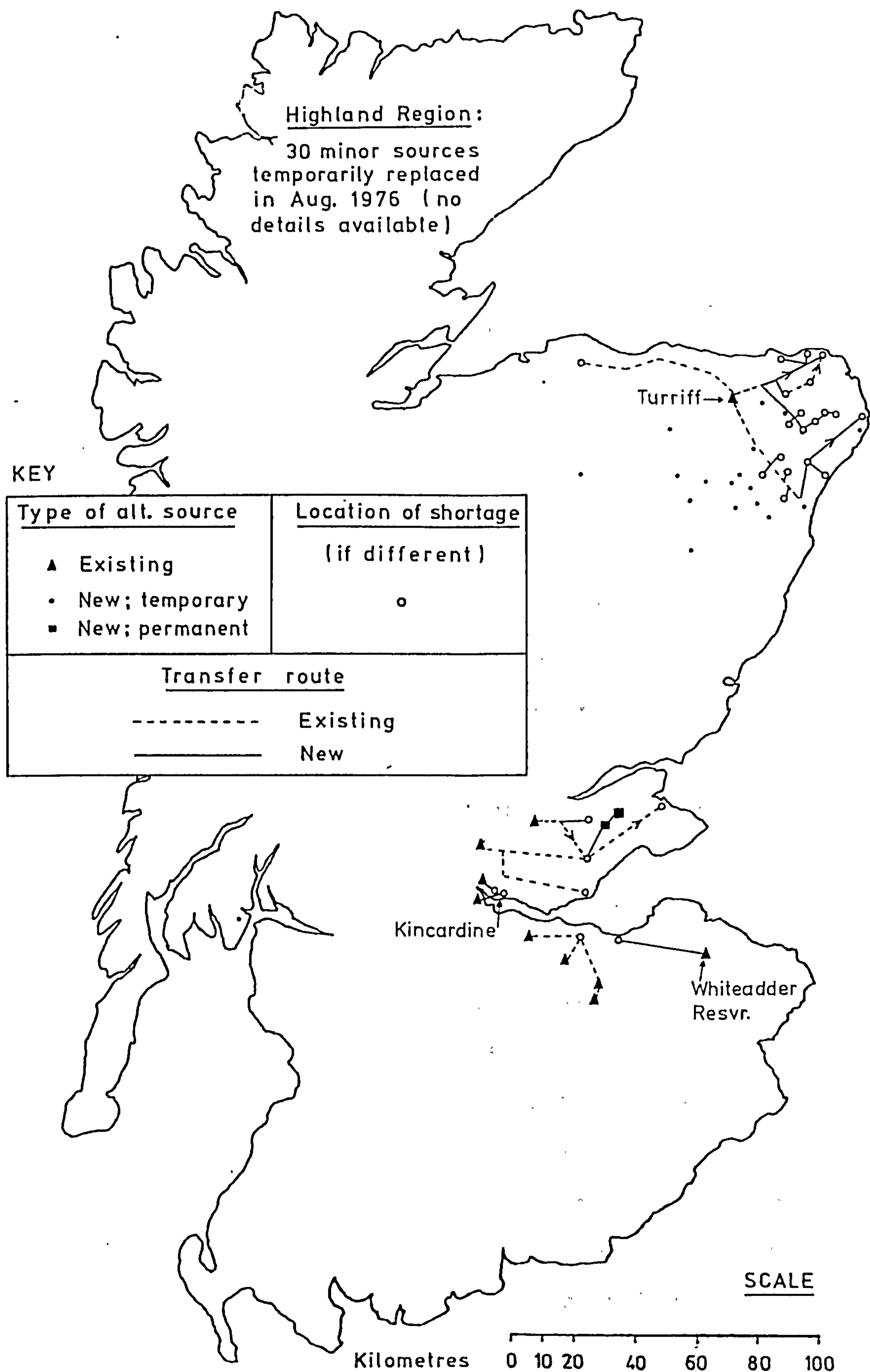
the Fife and Kinross Water Board placed notices in the local press warning consumers of increased discolouration, and a consequent increased chlorination of some supplies. They also stressed that such water was "not harmful to health", and that taps should not be run to obtain clearer water.

The second type of alteration to water quality involves somewhat limited direct effects on consumers, although the specific requirements of some industries can present particular problems. Changes of supply source do affect consumers indirectly in that water authorities can run up a large expenditure in effecting them. The types of action concerned, whose incidences can be located on Fig. 3.21, can be sub-divided into two categories of change in supply, ie; (i) a change or reorganisation of existing supplies; and (ii) use of new sources of supply, be they temporary or permanent.

In the case of the former, the alternative supply may be from either the same water authority area, or a different one. The events of the 1970's include examples of both.

As regards intra-regional transfers of supply source, these can be relatively easy to effect, and thus occurred quite frequently in the period of concern. In Fife, because of the "networked" regional water supply system, transfers of water between different local supply systems were common in the period 1972-74 as Fig. 3.21 illustrates.

FIGURE 3.21 : The Use of Alternatives to Normal System Supply Sources and the Corresponding Transfers of Water in Scotland During the Period 1971-76



In one particular instance, the proposal to partially switch the supply to the Leven area from the Glendevon to the Glenfarg Reservoir caused concern for a whisky manufacturing company. Their complaint that the higher magnesium content and "hardness" of water from the alternative source would detrimentally affect whisky production was considered by the water board and a compromise solution was reached.

Greater difficulties can occur when alternative sources are not linked into the same supply network. For instance, in 1973, the Edinburgh and Midlothian district of the South East of Scotland Water Board was already utilising a total of around 20 Ml per day from three small emergency reservoirs, and a further 2 ml per day on a temporary basis from neighbouring West Lothian. Then, as illustrated on Fig. 3.21, in order to obtain further emergency supplies, a new pipeline had to be constructed, allowing the daily transfer of 5 Ml from the Whiteadder Reservoir (serving East Lothian) to Midlothian, where Gladhouse Reservoir was experiencing difficulty in fulfilling its supply function.

Another case occurred in the Grampian Region prior to the completion of a system of regional trunk mains in 1975. Three years previously, the Fedderate Reservoir (supplying Fraserburgh) had to be replenished by pumping water from the Turriff intake on the R. Deveron, by way of a specially constructed pipeline. As Fig. 3.21 indicates, the latter source was used to supplement failing supplies in several



parts of the Grampian Region. Some of these temporary connections were eventually made permanent.

Temporary transfers of water on an inter-regional basis were much less common during the water shortages of the 1970's. Such transfers between water authority areas can present difficult problems of administrative, financial and technical natures, especially when conditions of shortage are widespread, as in the period 1972-73. The only example of this type to be found involved the construction of two temporary pipelines from the Mid-Scotland to the Fife and Kinross Water Board area, one of which had to cross the Firth of Forth at Kincardine. These emergency supplies involving a total of 10 Ml per day were needed to supply two electricity generating stations in Fife.

The remaining category of alternative sources of supply is that involving completely new and previously undeveloped sources. Fig. 3.21 indicates that those locations where temporary new sources were utilised occurred exclusively in the Grampian and Highland Regions. In such parts of the country there are large reserves of untapped resources to meet the relatively small requirements, compared with the situation in the more densely populated parts of Central Scotland. Consequently, suitable temporary sources, which could be easily exploited, were often found close to the centres of shortage in the northern areas.

Contrastingly, water boards in more central areas, and in particular in the Lothians and Fife looked for new sources

of water which could be utilised on a permanent basis. The possibilities of developing boreholes, springs and mine waters as part of the water supply system were investigated by the water boards in these areas. Indeed, in Fife emergency boreholes (shown in Fig. 3.21) were in operation as early as November 1971, and on subsequent development were contributing  $10 \text{ Ml d}^{-1}$ , or 9%, to the areas total requirements by 1973.

In summary, it would seem to be the case that many of the problems of water shortage experienced in the 1970's were overcome by transference of water from areas of more plentiful supply. Therefore, further integration of distribution networks of intra and inter-regional water supplies could be proposed as one method of limiting the impacts of future water shortages. Further consideration is given to this matter in Section 4.3.4.

#### 3.4.4.3 Environmental Effects

In times of actual or threatened water shortage, it is common practice to protect public supplies by making increased demands on available water resources. The two main activities concerned in this section are;

(i) the increase of abstraction rates from existing sources of abundant supply, and the use of additional temporary abstractions;

(ii) reductions in compensation water outflows from public water supply reservoirs.



Generally, in normal circumstances, these matters are bound by individual statutory conditions and limits. Therefore, any alterations sought by water authorities usually require a high level of administrative clearance. The Water (Scotland) Acts of 1946 and 1958 require that water boards seek the permission of the Secretary of State for Scotland to change such statutory conditions, by way of an Emergency Order. Such an Order is granted if the Secretary of State is,

"satisfied that the water authorities are faced with a serious deficiency in their supplies occasioned by an exceptional shortage of rain".

During the 1971-76 period, no fewer than eighteen Emergency Orders, or extensions thereof, were issued (Scottish Development Department, 1980). Such a number within a 6-year period is an unprecedented occurrence. Details of all 18 are listed separately for the two categories above in Tables 3.8 and 3.9 respectively. The locations affected can be located on Fig. 3.22, along with similar cases where in fact no Emergency Order was necessary. This tended to occur in the case of reduced reservoir compensation outflows, when water authorities reached voluntary agreements with other interested or affected parties; and in the case of temporary abstractions when existing statutory regulations are not interfered with.

The effects of the two types of measure on river flows are now discussed in turn.



**FIGURE 3.22 : Temporary New River Abstractions and Reduced Reservoir Compensation Flows Implemented (Both With and Without an Emergency Order (E.O.) ) in Scotland in the Period 1971-76 (further details in Tables 3.8 and 3.9)**

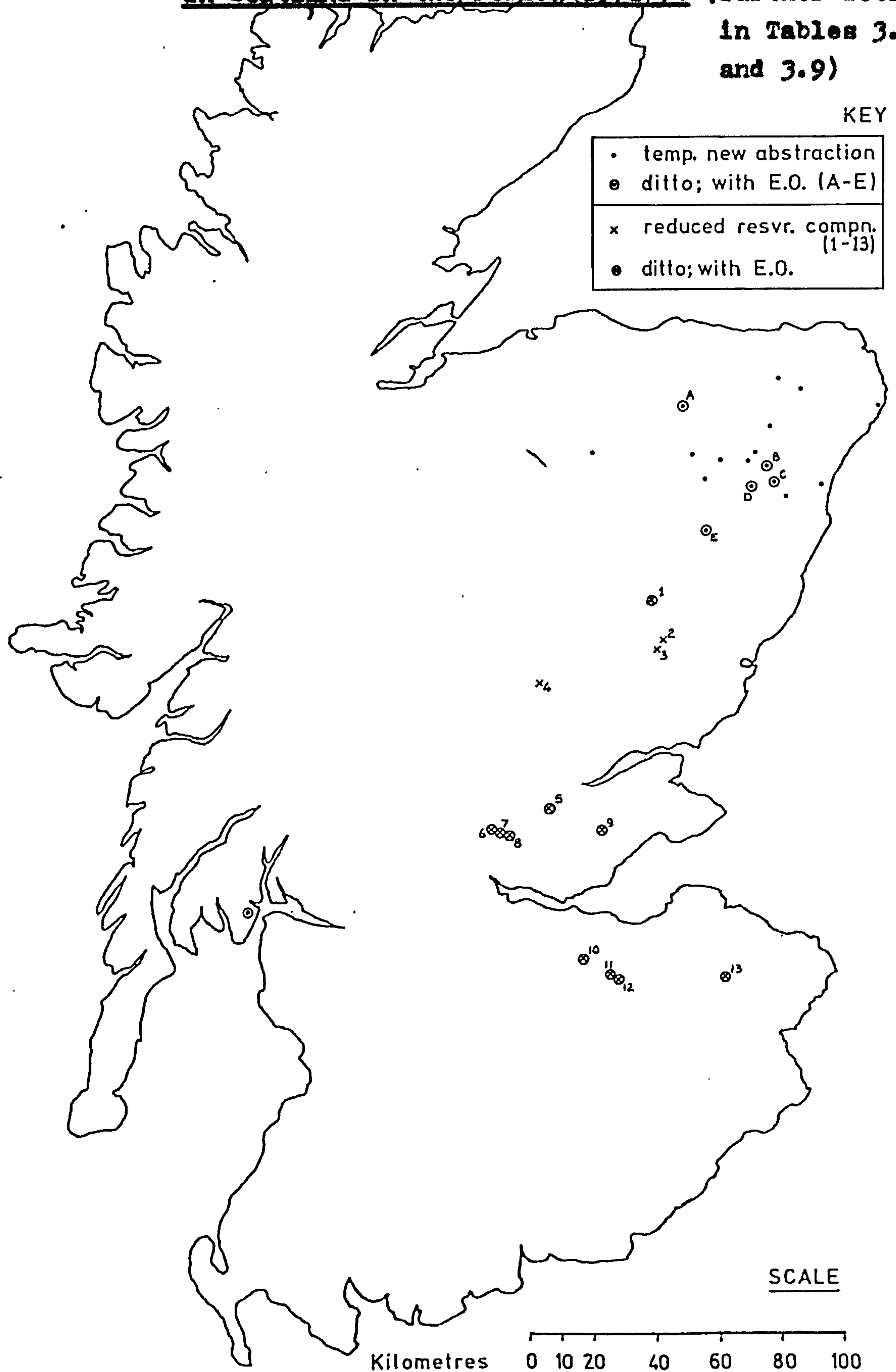


TABLE 3.8 : Temporary River Abstractions Requiring an  
Emergency Order During the 1971-76 Period  
in Scotland (see Fig. 3.22 for locations)

Ref. (see Fig.3.22)	Location	Years affected (19___)	River	Permitted abstraction (Ml d <sup>-1</sup> )
A	Huntly	71-75	Deveron	2.27
B	Inverurie	71, 72	Urie	0.32
C	Kintore	71	Don	0.14
D	Kemnay	73	Don	0.20
E	Kincardine O'Neil	71	Dee	0.05

(1) Temporary abstraction measures

All Emergency Orders, and most of all the other measures taken during the 1971-76 period involving temporary additional abstractions, occurred in the Grampian Region as Fig. 3.22 indicates. As was shown earlier, on Fig. 3.18, water supply in this area is rather heavily reliant on direct supply from springs. Several minor sources were unable to meet their expected supply capabilities, and hence the supply to the towns shown on Fig. 3.22, ie. (A) Huntly, (B) Inverurie, (C) Kintore, (D) Kemnay and (E) Kincardine O'Neil, had to be supplemented by means of Emergency Orders. As already indicated, on Fig. 3.21, numerous other temporary sources of supply were utilised in the Grampian Region in the 1970's. As an example of the wide variety of the types of alternative source used, the eleven operational on 21.11.72 in the Grampian Region comprised of 4 field drains, 2 springs, 1 tile drain, 1 old well and 3 streams.

The quantities of water involved in such cases are unknown, however in those instances where Emergency Orders were granted the magnitude of the temporary abstractions can be investigated. The "North East of Scotland Water Board (River Deveron) (Emergency) Water Order 1971" can be used as an example (Scottish Development Department, 1980). This particular statutory instrument was first enforced on 27.5.71 and its conditions applied for 36 months in the period up to March, 1975. It allowed the abstraction of



4.5 Ml "in any day of 24 hours reckoned from midnight" from the R. Deveron at Huntly (location (A) on Fig. 3.22). This quantity of water represents an average constant flow of  $26 \text{ l s}^{-1}$ . If it is assumed that the daily allocation was abstracted over a 12-hour interval, this averages out at  $52 \text{ l s}^{-1}$ . From Figs. F.1 and F.2, the 1 and 5 percentile flows at this location on the R. Deveron can be calculated at 1105 and 1360  $\text{l s}^{-1}$  respectively. Thus, this average maximum allowable abstraction rate of  $52 \text{ l s}^{-1}$  would represent less than 5% of either of these low flow values.

Indeed, as all four other temporary abstractions requiring an Emergency Order involved even smaller proportions of the relevant 1 and 5 percentile flows, it can be concluded that detrimental impacts on river systems due to these practices would be minimal.

## (2) Reduced compensation flows

These measures were implemented only on reservoirs in a well defined geographical area, comprising the eastern parts of Tayside and Central Regions, Fife, Lothian and Berwickshire, as Fig. 3.22 illustrates. As indicated earlier, public water supply is predominantly dependent on impounding reservoirs in these areas. In fact over half of the reservoirs supplying Lothian and Fife, capable of supplying more than 2 Ml per day, were subject to compensation water reductions between the years 1971 and 1976.

Of the 13 reservoirs affected over the country, all but 3 in Tayside had Emergency Orders imposed at some time.

TABLE 3.9 : Reservoir Compensation Flow Reductions in Scotland  
During the 1971-76 Period (see Fig.3.22 for Locations)

Ref. No. (see Fig. 3.22)	Name of reser- voir	Years Affected (19___)	Normal Compen- sation flow (l s <sup>-1</sup> )	Reduced flow (l s <sup>-1</sup> )	% reduc- -tion	Estimated %ile flow (l s <sup>-1</sup> )	
						5	1
1	Loch Lee	76	342	132	62	295	253
2	Glen Ogil } Den of Ogil }	73	138	69	50	73	63
3		75	138	0	100		
4	L.Benachally	73	92*	26	72	10.5	7.5
		75, 76		10	89		
5	Glenfarg	71, 72	22	7	67	17	14
6	Glendevon } Glenquey } Glensherrup }	71-73	297	98	67	164	139
7							
8							
9	Lothrie	71, 71	92	50	46	57	42
10	Glencorse	73	75	53	30	26	20
11	Edgelaw } Roseberry }	73	229	149	35	189	157
12							
13	Watch Water	73	26	13	50	30	25

\* This is the summer figure, it is 46 l s<sup>-1</sup> in winter.

Details of all 13 are summarised in Table 3.9. Some of the compensation water reductions, which range from 30 to 100%, would appear to be of rather severe proportions. However, they must also be considered in the light of the existing circumstances, ie. low flows and threatened public water supply failures.

Use of Figs. F.1 and F.2 has provided estimates of the potential natural 1 and 5 percentile flows from the catchment areas of individual reservoirs. These estimated low flow yields are listed in Table 3.9. In almost all cases the statutory normal compensation flows exceed the estimated 5 percentile levels, the only exception, by a small degree, being Watch Water Reservoir.

Of the reduced reservoir outflow levels which were enforced, only 2 were greater than the corresponding 5 percentile flow, and of the nine that were smaller, six were also smaller than the relevant 1 percentile yield. Although this represents a considerable variation in the reduced level of compensation flows, it can generally be said that most of them correspond, albeit very approximately, to natural flows around the 1 percentile level. Such reduced outflows, unless decreased to zero can be considered to approximate the natural situation in low flow conditions. However, the strikingly unnatural feature about them is their duration.

In Section 2.4.4.2 it was shown that in droughty low flow conditions, the duration of 1 percentile flows in the East of Scotland was of the order of a few weeks in a year.



The reservoir compensation flow reductions quoted above tended to last for typically 6 months or more. Therefore, it can generally be concluded that watercourses immediately downstream of the thirteen reservoirs could have been affected more so than comparable natural streams in terms of the very prolonged nature of flow levels around the 1 percentile mark.

There are some major exceptions to the above general case. These occur when compensation water arrangements are seasonally adjusted so that proportionately more water is released where low flows are more likely. For example, releases from Loch Benachally (No. 4 on Table 3.9 and Fig. 3.22) in summer, at  $92 \text{ l s}^{-1}$  are double those of the winter. Hence, as Table 3.9 reveals, a rather severe summer reduction in compensation flow of 89% results in a outflow still around the corresponding natural 5 percentile level.

A similar seasonal arrangement exists for the Fruid Reservoir on the upper reaches of the R. Tweed, where the May to September compensation flow, at  $206 \text{ l s}^{-1}$ , is double that of the winter months. In addition, a total of 220 ML is released in a series of "freshets" between May and October each year.

In some instances, "block grant releases" from supply reservoirs can be requested by River Purification Boards when river flows are low. For example, in the case of the latter reservoir above, the Tweed River Purification Board have a statutory entitlement to ask for the additional

release of up to 1000 Ml in any one year. In the low flow year of 1972, 55% of this quantity was released (Tweed River Purification Board, 1972).

Where these types of statutory conditions exist, river flows immediately downstream of impounding reservoirs can be maintained well above the corresponding natural low run-off yields. Of course, this effect of augmenting natural flow becomes proportionately less at greater distances downstream from such reservoirs. However, in conditions of drought and water shortage, these extra demands can increase the problems of managing certain water supply reservoirs.

#### 3.4.5 Summary of Impacts on Water Supply System Requirements

In summarising the impacts of the 1971-76 drought on consumer and environmental requirements in the sphere of public water supply activities, the following points are most noteworthy.

In terms of the reduced availability of water, the vast majority of the population of eastern Scotland were subjected to hosepipe bans. Such prohibitions, of durations up to twelve months and more, were applied widely over the 1971 - 76 period. However, the force of their application, and that of the attendant publicity campaigns varied greatly. Whereas some water authorities used little more than the statutorily required press notices, others employed television advertisements and door to door leaflet drops



to publicise their hosepipe bans and requests for reduced consumption.

Severe forms of water rationing were limited to the Grampian Region, where water was transported by road in the autumns of 1971, 72 and 73 to up to around thirty rural communities in the area.

Notable detrimental changes in the quality of water available to consumers occurred when reservoir levels fell to around 20% of maximum capacity. Although such critical storage levels caused water authorities to use alternative supplies in many areas, the resulting inconveniences concerned only specialised industrial water requirements.

In the north-east, such alternative supplies were often resources not normally utilised by water boards. However, the quantities of water involved in all abstractions requiring an Emergency Order were so small as to involve a negligible impact on the affected aquatic environment. It is possible however, that some adverse environmental impacts were suffered in some of the 13 streams whose reservoir compensation flow was reduced. This is so not only in relation to the severity of some reductions, but particularly as regards their duration, of typically six to twelve months.

The effectiveness of all the actions whose impacts on water demands have been considered in Section 3, is assessed in terms of their suitability for drought management, in Section 4. The other major concerns of this Section,



which now follows, are the related matters pertaining to the planning of water resources in relation to drought in Scotland. Section 4 considers these topics with specific regard to reservoired water supply systems, since the greatest range and geographical extent of drought impacts suffered during the 1971-76 period were associated with this type of water resource.

SECTION 4

AN ASSESSMENT OF WATER RESOURCE PLANNING  
AND MANAGEMENT IN SCOTLAND IN  
RELATION TO DROUGHT

#### 4.1 FURTHER CONSIDERATION OF THE SUPPLY/DEMAND CONCEPT OF DROUGHT

Since this Section considers the "supply" and "demand" concept of drought further, by drawing together the relevant parts of Section 2 and Section 3 respectively, it would be appropriate to firstly recall some earlier comments on drought assessment. In Section 2, two different types of measure of deviation affecting the "supply" element of drought were investigated and subsequently utilised. These were;

(i) variations from normal measured in absolute or proportionate terms;

(ii) variations from normal assessed by probabilities of recurrence.

The use of these two indices of variation affecting "supply" is now discussed with particular regard to the "demand" feature of drought.

For the purposes of demonstration, it is appropriate to consider two parts of the world which could be said to have suffered drought in the early 1970's, ie. the East of Scotland and the Sahel region in West Africa. Table 4.1 below presents details of low annual run-off events for; the R. Dee catchment measured at Woodend in the Grampian Region, which has the longest river flow record available in Scotland, of 50 years; and the Melmele a Delep located in Chad, in one of the wetter parts of the desert margin region of Sahel. Data concerning this latter river are taken from Rodier (1975).



Median annual rainfalls for the two catchments are around 1300 and 800mm respectively.

TABLE 4.1 : Comparison of Low Annual Run-Off Events for the R. Dee in Scotland and the Melmele a Delep in Chad.

Watercourse	Catchment area (Km <sup>2</sup> )	Year	Annual Run-Off (mm)	% of Median Annual Run-Off	Recurrence Probability
R. Dee	1370	1973	666	66.0	0.02
Melmele a Delep	1750	1972	4.7	29.4	0.05

Using method (i) above, concerned with deviations from average, or normal, when a comparison is made between the two events above, it would appear that hydrologic drought, as such, in the Sahel was much more severe than in eastern Scotland in the early 1970's. A further implication of using this basis of assessing drought is that severe events would appear to be much more common in the former area. However, since conditions of water shortage and "drought", as measured in this example, are to be expected more frequently in the desert margin region, a given percentage deviation in annual run-off in the Sahel is much less "abnormal" than a similar event in eastern Scotland. This lack of an adequate measure of "abnormality", as required by the preferred definition of drought, means that an extreme event in Scotland such as that above, corresponding to a recurrence probability of 0.02, may not be classed as a "drought" on the basis of the percentage deviation from normal run-off.

Contrastingly, if a direct measure of "abnormality", ie. recurrence probability, is used to assess drought, then

it would appear that the R. Dee catchment in Scotland suffered a more severe drought than that affecting the Melmele a Delep in the Sahel, in the 1970's. Taken to its logical conclusion, this approach means that Scotland, and anywhere else in the world for that matter, has, in the long term, the same incidence of "drought" as the Sahel. This contention would appear to be obviously inadequate. Therefore, neither of these two approaches above seem particularly appropriate in relation to the total concept of drought as originally defined.

If the "demand" part of the drought equation is brought into consideration, then the situation can be more successfully explained. For a given water supply-demand system, there can be found an optimal level of adjustment of supply, be it natural or influenced by storage reservoirs for example, to suit the existing patterns of demand. When adequate climatic or hydrologic data exist, this can be done by assessing variations in run-off and hence supply, and the requirements and flexibility of demands, and then deriving a compatible solution. Calibration and optimisation of such a system is probably most readily done by a form of cost-benefit analysis.

In an optimal supply-demand situation, there will be a known probability of failure of supply, ie. drought. The position of this optimum in the supply and demand equation will determine the incidence of drought.

Comparison of two different regions, say west and east central Scotland, where the former has a higher and less variable rainfall (see Fig. 2.6), can give further insight



into this matter. In a hypothetical pair of identical regimes where water demands and potential losses due to shortage are the same in each area, then to guarantee equal public water supply levels would cost more in the latter since, eg. a larger reservoir capacity would be required. The economic optima, determined by cost-benefit analysis would be different for the two regions, such that the east would have to settle for a higher, but known, incidence of drought. Consequently, a rainfall or run-off event of a given recurrence probability over the whole country would perhaps cause a drought in the east, but not in the west of Scotland.

Although this hypothetical example is far from reality, it does indicate the difficulties in attaching a suitable measure of severity to the phenomenon of drought. For example, the decile range system developed by Gibbs and Maher (1967) provides a useful measure of the abnormality affecting supply, however the severity of drought associated with each recurrence probability or decile, will vary from place to place. Therefore, a given drought event could be given a decile or probability measure, but along with a corresponding index of severity applicable to specific regions or areas.

In the real world, in relation to the optimisation of water supply and demand, it is usually more appropriate to make adjustments to the former rather than alter water requirements. The scope of these latter adjustments would generally seem to be restricted to a temporary short term basis rather than be part of a long term measure. As



Subrahmanyam (1967) stresses, drought is dependent on established demands for water. It could be argued that an established economy represents a near-optimal water supply/demand balance, since its development would not have been possible if demands on water resources were inappropriately high. Indeed, this assumption is made in some drought studies. For example, Russel et al (1970), in their study to develop an optimal planning model for public water supply in Massachusetts, measured a water supply shortage (S) in any given year by,

$$S = \frac{D - V}{D} \dots\dots\dots 5$$

where D = potential demand.

V = supply from the normal sources.

They also made the assumption that the reservoirs involved had actual "safe yields" corresponding to those calculated by water authorities on the basis of average rainfall over the dry period from 1908-11 inclusive.

The difficulty in assessing the desired supply/demand balance, or "safe yield", is compounded by the further considerations that;

- (i) demands for water have tended to rise gradually in recent years and may continue to do so;
- (ii) the corresponding adjustments made to supply capabilities tend to follow a "stepped" rather than gradual path;
- (iii) there is no guarantee that past variation in hydrological variables will represent that of the future.

All these factors tend to render a reliable assessment of an optimal probability of failure of supply difficult to

make. Therefore, in a drought-type situation, the proportions of water shortage attributable to either an abnormally low supply, or an unduly high demand are often difficult to estimate. Nevertheless, it is most desirable to base water demands on the best available optimal level of adjustment to the existing pattern and extent of hydrological variation. The remainder of this section considers the techniques and policies used for the planning and management of water resources in Scotland, as regards, for example, the degree of adjustment of water supply capabilities and the level of demands made, to suit climatic and hydrologic variation. As before, the two groups of demands identified earlier, ie. those associated with water supply provision and waste water disposal are treated separately, with a brief discussion concerning the latter coming first.

#### 4.2 DROUGHT MANAGEMENT OF WASTE WATER DISPOSAL SYSTEMS AND RIVER WATER QUALITY

Various aspects of the deterioration of water quality caused by low river flows have been described in Section 3. The amelioration of such adverse conditions and any associated environmental problems could be achieved in several ways. The possible solutions fall into three categories, namely;

(i) the retention of polluting effluents during low flow spells;



(ii) the retention of water for release during low flows;  
(iii) the reduction, or improved quality of effluent discharges, on a permanent basis.

The choice between such options has been facilitated by mathematical models developed by Tapp(1976) and Vilella (1973). The former author simulates the instream effects of employing schemes based on the first approach above. Similarly, Vilella uses simulated D.O. levels to choose optimal solutions based on the remaining two approaches, by use of both ecological and economic criteria. Such methodologies could be very useful where specific data concerning these criteria are readily available, but this is usually not the case, as the examples investigated in Section 3 indicate. Although the drought "supply" element, ie. river flow, and its effects on water quality parameters can be quantified and examined in detail, as the example in Section 3.3, pertaining to the R. Almond illustrates, the "demand" features are more difficult to specify. For instance, the full range of tolerances and requirements for the growth and development of fisheries in natural conditions are largely unknown (Food and Agriculture Organisation of the United Nations, 1969; and European Inland Fisheries Advisory Commission, 1973). In addition, environmental requirements, once specified, are difficult to quantify and incorporate in any economically-based analysis intended to optimise river management.

Apart from these difficulties in formulating and justifying a given management policy, in the existing legal and



administrative system in Scotland, River Purification Boards would have great problems in the area of their enforcement. Normal practice for these Boards is to set acceptable water quality standards for given river locations, and to take necessary action if such limits are exceeded. For example, in one of the cases described in Section 3.2.3, concerning extreme low flow levels in the Peffer Burn West in East Lothian, the Forth River Purification Board obtained a Control Order under the Spray Irrigation (Scotland) Act, 1964, on 15.11.73, to license, and if necessary limit, abstractions for irrigation in the area.

In cases involving a deterioration in water quality associated with the presence of sewage or other effluents, any corrective action initiated by River Purification Boards is usually confined to type (iii) above. For example, representations made to the dischargers of industrial and sewage pollutants on the R. Don by the North East River Purification Board (1976) achieved some success in lowering the Biological Oxygen Demand of offending effluents. The N.E.R.P.B. (1977) however, state that such improvements are still short of what is required to achieve<sup>ie</sup> their desired standards. In such circumstances, legal action can be taken against polluters contravening standards set for effluent quality, and this was considered by the N.E.R.P.B. (1976), but not implemented. Such action cannot be regarded as particularly constructive as a means of solving immediate problems, and a procedure of negotiation between relevant parties is usually more practical.

In the light of the above considerations, there is a possible case for having well-defined river management policies geared at maintaining water quality in times of low flow. However, as indicated earlier, their justification and enforceability are very much dependent on there being specific ecological and economic criteria for the determination of the environmental requirements to be placed on a river system. In conclusion therefore, it must be said that detailed information in this field is required if the feasibility and applicability of any water quality management policy is to be assessed.

#### 4.3 WATER SUPPLY SYSTEM PLANNING IN RELATION TO DROUGHT

The remainder of this Section is devoted to the consideration of firstly, the planning and secondly, the management of reservoired water supplies in relation to drought. "Planning" here is defined as the strategies and policies determining long term usage and development of both existing and future water supply sources.

##### 4.3.1 Balancing Supply and Demand - Reliable Yields

All water supply sources in use in Scotland capable of providing 2Ml per day or more, have an official "reliable yield", or in the case of river intakes a "maximum permissible



abstraction". The sources and yields are all listed by the Scottish Development Department (S.D.D.) (1973a).

In the case of impounding reservoirs, most of these yields are based on rainfall variations, which seems reasonable, because of the almost complete lack of river flow data prior to 1950. Perhaps more unusual is the fact that the chief index of variation adopted is the deviation from average involved in the mean of the three driest consecutive years' rainfall. The first reference to this standard measure was made by the Royal Commission on Water Supply in 1867. Over the following years, several suitable guideline values have been suggested. For example, Binnie (1892) calculated the generalised average value for the mean of the three driest years rainfall in Britain to be 80% of the long term average. Thirty-two years later, Glasspoole (1924) produced a similarly-based figure of 85%, but noted regional variation in the range of 75-91%.

Such values, representing minimum three-year rainfall are "considered reasonably safe" (S.D.D., 1973a) as a basis for the drought condition which is used to determine the reliable yield of reservoirs. As regards the precise reliability of such yields, only crudely estimated return periods are offered. For example, the S.D.D. (1973b) suggest that an event corresponding to 80% of average rainfall over a three-year period has a return period of once or twice in 100 years.

This method of assessing the reliable yield of reservoirs in Scotland can be criticised for several reasons, these being as follows.



(i) The use of rainfall measurements.

As was revealed for the 92-year record derived for Gladhouse Reservoir's catchment, there can be a relation between rainfall and run-off variability, but similar degrees of variation do not necessarily occur simultaneously. Thus, the lowest three years' rainfall may not accurately represent the lowest run-off period. However, where no estimates of run-off exist, then the use of the somewhat indirect influence of rainfall on reservoir storage has to be used.

(ii) The use of a three-year period.

Perhaps historical evidence led to the suggestion that it was drought over a three-year period which could have the most detrimental effect on reservoired water supplies. However, it is now clear that severe water shortages can result from much shorter periods of rainfall deficiency. For example, in the drought of 1959 in south-east Scotland, the Talla Reservoir supplying Edinburgh, which was full in April, contained only 27 days supply after 5 months over which the rainfall was 68% of average (Lothian Region Water Supply Services, 1980). More recently, in 1975/6 the occurrence of 64% of average rainfall over a 16-month period caused severe water shortages in parts of England and Wales (Central Water Planning Unit, 1977). This evidence would suggest that a three year-period is much too long to represent the possible range of influence of climatic variation on reservoired water supplies.

(iii) The lack of a useful measure of recurrence probability.

Perhaps by basing reliable yields on drought conditions

corresponding to the driest-ever three-year period, the original intention was to achieve near 100% reliability. Consideration of the duration of the data base could yield an estimated return period for such an event. However, this would produce only one estimate for one level of shortage severity, ie. complete failure of supply, based on one time period, ie. three years. Such a recurrence probability would therefore be of extremely limited usefulness.

#### 4.3.2 An Assessment of the Applicability of Official Reliable Yields

An insight into the applicability of official reliable yields to drought conditions can be gained from consideration of events during the 1971-76 period. Investigation of the first and driest three years of this spell would be particularly appropriate, as reliable yields are assessed by events of the same duration. An isohyet map, based on 100 selected stations, displaying the percent of average (1941-70) rainfall over the 3-year period, 1971-73, is shown in Fig. 2.3. The area with less than 80% of the average rainfall closely corresponds to what could be termed the eastern half of Scotland.

As the reliable yield of all reservoirs is calculated on the standard basis described earlier, comparison between different water resources is feasible. A ratio relating actual and projected levels of demand to reliable yields was



used by Russel et al (1970) to assess the adequacy of water supply reservoirs in Massachussets, U.S.A. In this state, reservoir reliable yields are adjusted to drought conditions associated with a four-year minimum rainfall. Such a technique allows similar assessments to be made in the case involved here. Fig. 4.1 displays the system adequacy ratio (S.A R ) given by;

$$\frac{\text{reliable yield}}{\text{pre-drought normal system supply}} \dots\dots\dots 6$$

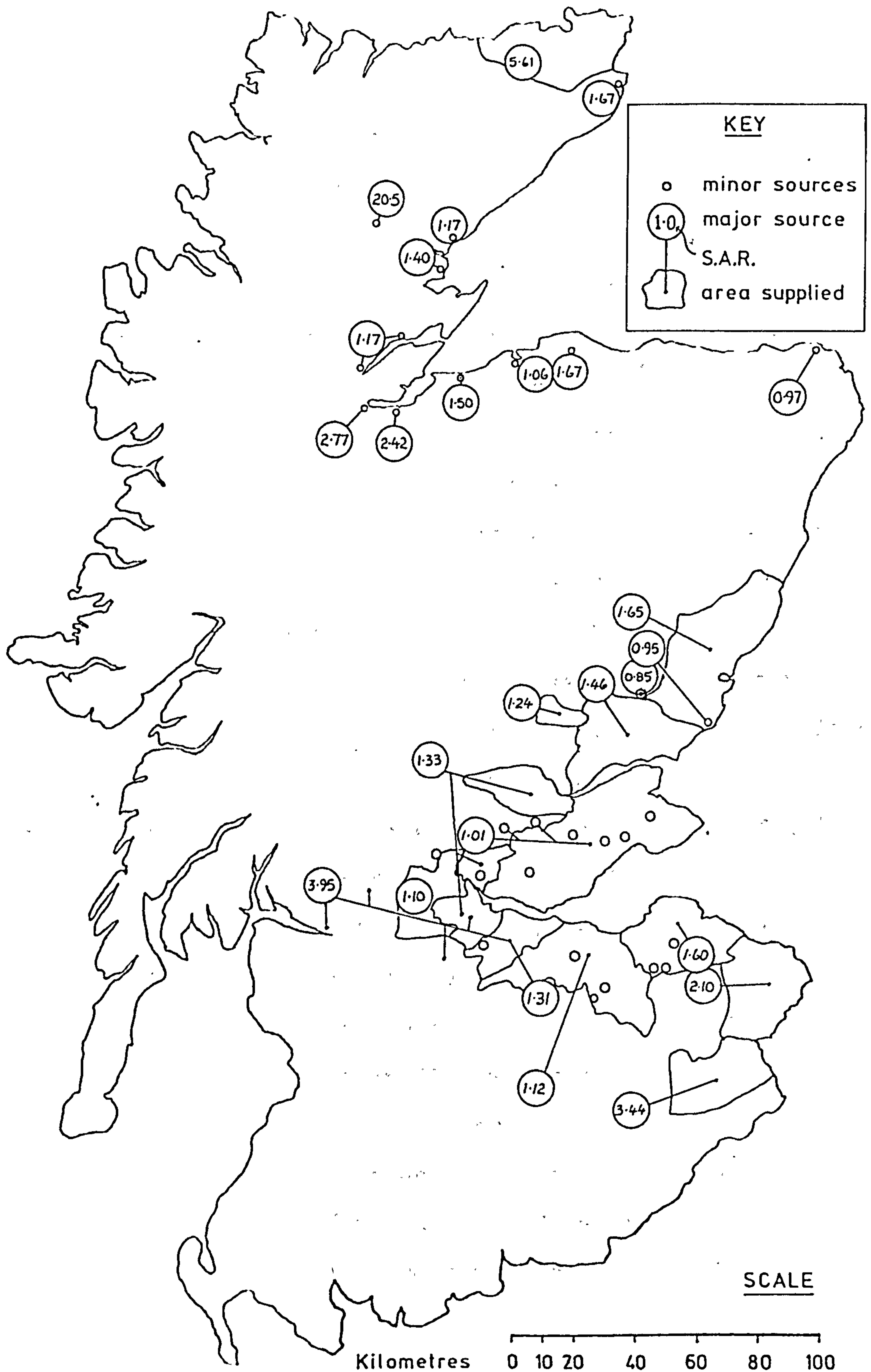
for the major reservoired supply systems serving distinct areas in eastern Scotland. This "system adequacy ratio" for individual supply areas is shown in the connecting large circles which represent the locations of the major sources of supply. Smaller circles indicate the whereabouts of a given area's minor supply sources. The SAR values refer to the year 1971. For system adequacy ratios around 1, the reliable supply capability is very similar to actual requirements, and the higher the value of this ratio, the greater is the surplus supply capacity above the 1971 demands.

It would be expected that those supply systems with greater surplus supply capacities would have suffered less from actual and potential water shortages in the early 1970's. Indeed, Russel et al identified and investigated relationships between SAR values, and the water shortages and consequent economic losses incurred in the drought of 1962-66 in the north-east of the U.S.A.

Two main examples can be found to support the above expectation. For instance, in two areas whose supply sources



**FIGURE 4.1 : The 1971 System Adequacy Ratios (SAR's) for Discrete Water Supply Areas Served by Impounding Reservoirs in the East of Scotland**



received around 75% of average rainfall over the 1971-73 period, ie. that around Dundee in Tayside, and East Lothian, there were absolutely no water restrictions enforced. This can be explained by the relatively high system adequacy ratios, of 1.46 and 1.60 respectively for these two districts. Conversely, consumers in supply areas where the value of this ratio was around 1, ie. Fife, Edinburgh and Midlothian, parts of Angus in Tayside, and Fraserburgh in Grampian, tended to suffer the most severe water restrictions as shown in Section 3.3.4 and Figs. 3.20.1 to 3.20.6.

Many exceptions to this expected pattern are apparent. In several areas with a surplus supply capacity in 1971, water restrictions and other measures to conserve reservoired supplies were enforced during a three-year period when reservoir catchment areas received around 80% of average rainfall. Instances of this somewhat unexpected phenomenon occurred over all eastern parts of Scotland, from the Highland Region to the Borders. Indeed, the most notable example occurred in Berwickshire in this latter region. The official reliable yield of the Watch Water Reservoir involved a surplus supply capacity of 110% in 1971, ie. a system adequacy ratio of 2.1. However, only two years later, in 1973, hose-pipe restrictions were in force for 10 months (see Fig. 3.20.3), and the reservoir compensation flow was reduced by half for 6 months by way of an Emergency Order (see Fig. 3.22 and Table 3.9). Even taking into account that the 1971-73 rainfall was just over 75% of the 1941-70 average, it is rather perturbing that a reservoir with such a seemingly large



surplus in supply capacity encountered such difficulties. Further concern is raised by the fact that neighbouring East Lothian, whose reservoirs received around 70% of average rainfall, and whose surplus supply capacity was much smaller at 60%, suffered no water restrictions whatsoever.

Other reservoirs whose catchments typically received 75-80% of average rainfall over the years 1971-73, whose supply areas suffered water restrictions, and whose 1971 system adequacy ratio (shown in brackets) was substantially above unity, include Loch Benachally (1.24) and Loch Lee (1.65) in Tayside, Glenlatterach Reservoir (1.67) in Grampian and Loch Calder (5.61) in Caithness. If, supposing that all these, and possibly other reservoirs, happened to have little or no surplus supply capacity during the drought period, then there is little doubt that water shortages and the subsequent restrictions and rationing of use would have been much more severe than they actually were.

These considerations provide evidence to support the contention that the "reliable yields" used to calculate the system adequacy ratios above may not be very useful in that; (i) they do not seem to correspond well to the occurrence of 80% of average rainfall over a three-year period; and (ii) the applicability of this standard method of derivation seems somewhat limited.

#### 4.3.3 Temporal Variation of System Adequacy Ratios

It is already apparent from Fig. 4.1 that most 1971 system adequacy ratios in eastern Scotland were greater than

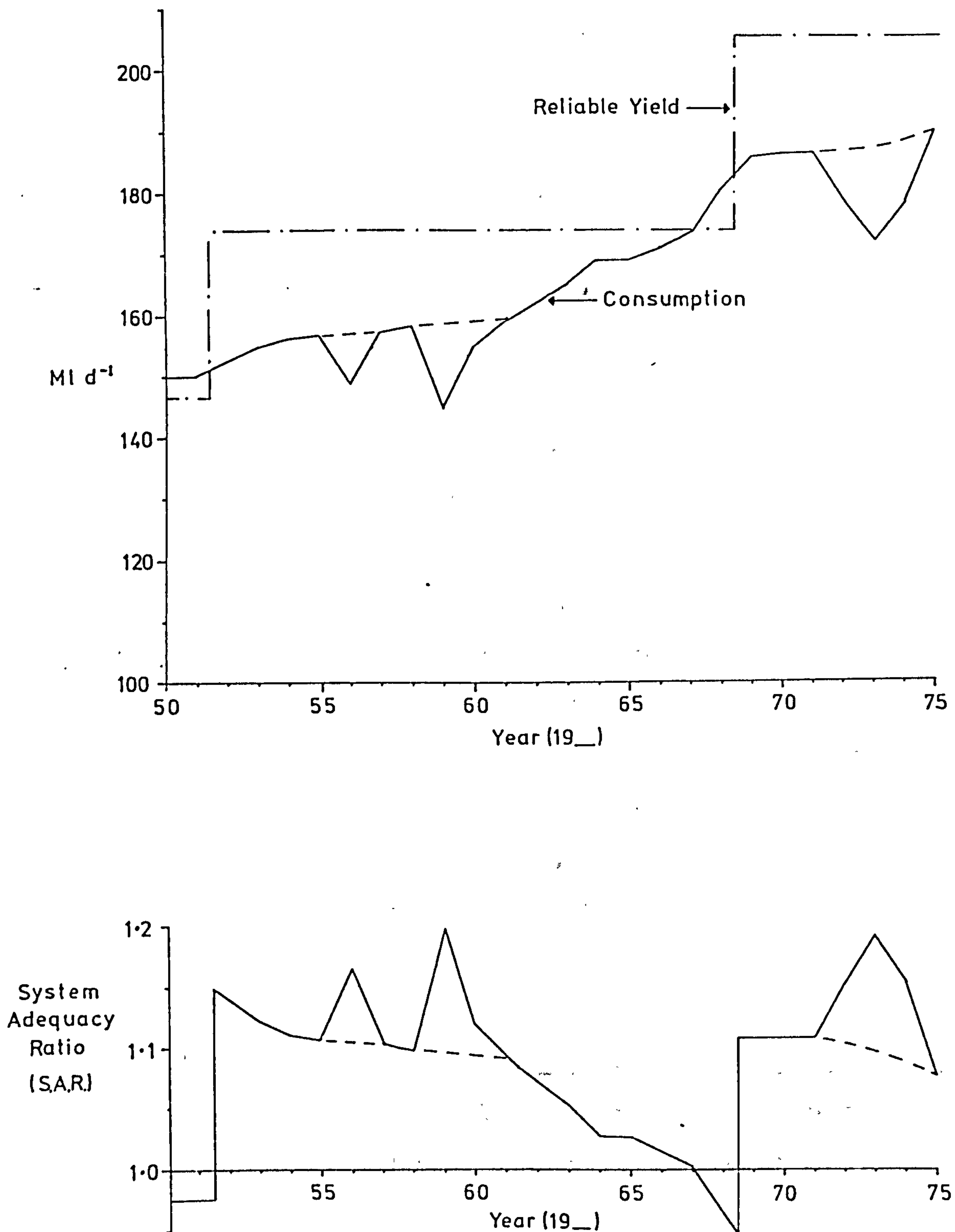


unity. There is a wide geographical variation in values from around 1 and upwards. This is a result of the "stepped" nature of the development of new water supply sources. For example, when a new supply reservoir is built, the system adequacy ratio can be greatly increased, then if water demands gradually rise over a period of years, the value of this ratio is correspondingly reduced, until a new source is developed, and so on. The values on Fig. 4.1 represent the stage at which each supply system is in the type of cycle described above.

An example of the general pattern of events is provided by Fig. 4.2. The data refer to the water supply system serving the Edinburgh and Midlothian area, which is 90% dependent on impounding reservoirs. Water consumption, or demand, has generally increased in this area over the period shown, ie. 1950 to 1975. The drops in consumption during the years 1955/56, 1959/60 and 1972-74 were caused by water restrictions and other measures imposed in times of shortage. The dotted lines on Fig. 4.2 refer to the estimated potential demand during these periods.

The gradual rise in demand and the development of two new sources since 1950 have resulted in the system adequacy ratio varying from the extremes of 0.95 in 1969 to 1.15 in 1952. It is notable that this ratio was relatively high, ie. 1.1 or greater, directly preceeding the three periods of shortage. This can be regarded as fortunate for the former South East of Scotland Water Board and their consumers. If the climatic events of 1972-74 had occurred just

**FIGURE 4.2 : The Reliable Yield, Consumption, and System Adequacy Ratio for the Edinburgh and Midlothian Water Supply System from 1950 to 1975**



five years earlier, when the system adequacy was around 1 or less, the consequences could have been much more severe.

Another interesting feature to be noted from Fig. 4.2 is the temporary effect of reduced consumption, in years of shortage, on the system adequacy ratio. In 1959 for example, its value was increased from 1.1 to 1.2. This gives some indication of the importance of flexibility of consumption (or demand) for water resource planning and management in relation to drought.

As the above example shows, the timing and size of newly-developed water supply sources are crucial matters. Although it is in the interests of water authorities and their consumers to have a system adequacy ratio greater than or equal to one, it is also desirable to avoid excessively high values which could represent bad financial investment.

The reconciliation of these two aims was investigated by Russel et al (1970) who developed a mathematical "capacity expansion planning model for Municipal Water Supply Systems" for Massachusetts, U.S.A. This allows the development of rules for optimal planning decisions concerning the development of new water resources, which would represent the most profitable financial investments.

#### 4.3.4 System Adequacy Ratios and Regional Water Supply Systems

As an alternative or additional approach to the optimisation of the timing and size of new developments in



individual water supply systems, there is another which also allows system adequacy ratios to be kept relatively stable. This has the same effect of making the rate of increases in supply provision more in tune with those of demand. In essence, this other approach involves the spreading of such increases over a larger area of consumption, thus reducing the relative increase in the system adequacy ratios. A policy associated with such actions is commonly referred to as eg. a "regionalisation" of resources or a "water grid" development.

Such schemes can be attractive in that, by the long term "evening out" of supply and demand, there are potential economic gains to be made. In addition, this applies in conditions of drought, when short term local shortage can be overcome by a transfer of supplies from less-affected areas. Takeuchi (1973) suggests that there are considerable socio-political and economic advantages to be gained from using regional water exchange systems to combat water shortages in drought.

As indicated earlier in Section. 3.3.2.1, there has been a recent emphasis in Scotland in the networking of alternative supply sources on an intra-regional basis. However, inter-regional linkages are few. Apart from minor transfers of water which are legacies from changes in administrative boundaries and responsibilities, only two such schemes proper exist. Both have been implemented over the past thirteen years by the Central Scotland Water Development Board. The two sources which lie towards the west are

included in Fig. 4.1, namely, the Loch Turret scheme, which can serve parts of Tayside and Central Regions; and the Loch Lomond scheme, which can supply parts of Strathclyde, Central and Lothian Regions. The system adequacy ratios of the two schemes in 1971 were 1.33 and 3.95 respectively. It is noticeable that those eastern parts of the country partially supplied by these two sources, which received over 80% of average rainfall over the 1971-73 period, never suffered any water restrictions in those years.

Inevitably considerations such as this increase speculation about the desirability of water supply grids and linkages between regions. For instance, a member of the Lothian Region Water and Drainage Committee raised a motion on 6.9.76 to urge the Secretary of State for Scotland,

"to consider the development of a national water grid to combat future problems, drought or otherwise which may arise"

(Lothian Region Minutes, September, 1976).

This was also the case after the 1975/76 drought affecting England and Wales, with both Huntingdon (1977) and Crann (1977) being among those raising these issues. The latter author considers the matter in some detail and concludes that; (i) as a gain in permanent yield is required to justify expenditure on intra-regional supply networks, the merits and feasibility of establishing internal grids are limited; and (ii) inter-regional transfers are appropriate only if economically optimal as permanent features,



and that resultant effects in alleviating drought problems should be regarded as a "bonus".

As Crann neglects to note, in assessing alternative water supply schemes, surely such "bonus" benefits should be included in any analysis. What is still clear though, is that consideration of all permanent and temporary costs and benefits associated with inter-regional water supply networks could be used to find optimal degrees of linkage between water authority areas.

In a drought affecting a large area, inter-regional water transfer facilities may be of limited use. In such a situation, or one where no such links exist, it is the short-term flexibility of supply and demand within individual reservoired supply systems which determine their ability to survive a drought. These factors are now assessed in the following section dealing with drought management.

#### 4.4 DROUGHT MANAGEMENT OF RESERVOIRED WATER SUPPLY SYSTEMS

This section covering the "management" of reservoired water supplies considers the analysis and optimisation of supply and demand over the short term, ie. in actual or potential drought situations. Thus, the matters of most importance are the temporary flexibilities of both water supply capability and water demands.



#### 4.4.1 Statutory Powers and Legal Instruments Available to Water Authorities

Firstly, it would be most appropriate to consider the relevant measures and the associated legal statutes available to water authorities. The only direct power open to water authorities to limit water consumption is that provided by Section 59 of the Water (Scotland) Act of 1946, which states;

"If a water authority are of the opinion that a serious deficiency of water available for distribution by them exists, or is threatened, they may for such a period as they think necessary prohibit or restrict as respects the whole or any part of their limits of supply, the use for the purpose of watering private gardens or washing private motor cars of any water supplied by them and drawn through a hosepipe or similar apparatus".

Authorities enforcing such restrictions are required to give notice by publication in at least two newspapers circulating in the affected areas. Consequently, hosepipe bans are usually accompanied by some form of publicity aimed at reducing water consumption.

Further actions which may be taken to increase the supply, or alternatively decrease the consumption of water in times of shortage, generally require the approval of the Secretary of State for Scotland, unless some voluntary agreement is reached between all affected parties.

The Fourth Schedule of the 1946 Act makes provision for authorities to forego their statutory duty to supply

domestic water "constantly and at such a pressure as will cause the water to reach the topmost storey of every building", in times of drought, by special permission of the Secretary of State.

A later Act, ie. the Water Act, 1958 provides further powers, again at the discretion of the above government Minister who, in granting an Emergency Order should be,

"satisfied that by reason of an exceptional shortage of rain a serious deficiency of supplies of water in any locality exists or is threatened".

Section 1 of the 1958 Act makes provision for the authorisation of water authorities to take water from a new source, take more water from an existing source, or to reduce the amount of compensation water from reservoirs.

Section 2 enables orders to be made in similar circumstances, empowering authorities to supply water from tanks or standpipes, and to continue to levy their normal charges while so doing.

Proposed Emergency Orders, either under section, are required to be served on specified persons, and advertised widely. In instances where objections are lodged, the Secretary of State can either effect a public local enquiry, or as more commonly happens, he can make representations privately to overcome any problems.

#### 4.4.2 The Assessment of the Short Term Flexibility of Water Supply and Demand

The actions taken by the various authorities in the East of Scotland during the period 1971-76, which were



considered in relation to their impacts on environmental and consumer requirements in Section 3, will now be analysed from a water manager's point of view. The quantitative effects of the various water conservation measures will be assessed to gauge the flexibilities of the supply and consumption of water in different water authority areas.

The effects of either increasing supply, or decreasing consumption, once identified, can be grouped together for the purposes of measurement, as percentage reductions to normal system consumption. This is possible since, for example, a reduction in reservoir compensation outflow can be considered as an increase in the amount of water available for consumers, and hence savings will be made in normal system consumption. Similarly, the use of alternative sources of supply can be regarded as reducing demands made on permanent sources, and quantified as such.

In addition to its practicability, this orientation towards the requirements of the normal system consumption can be justified by consideration of a water authority's first duty under the 1946 Act, ie. to "provide a supply of wholesome water to every part of their limits of supply".

The reference consumption, or normal level of demand adopted was that occurring in the twelve months prior to any water restrictions being imposed, ie. usually 1971. This was used for the entire 1971-76 period, as the underlying trend of demand in most water board areas, in the few years prior to the drought, was one of no change. Fig. 4.2 illustrating the annual pattern of demand in Edinburgh and



Midlothian provides a typical example. In instances where a seasonal variation in demand is prevalent, the normal demand was gauged from the relevant months(s) of the standard reference year.

All estimates of variations in supply capacity and consumption of water are made using data provided by the various water authorities, usually in the form of graphs or tables of weekly consumption; and details of all Emergency Orders in the 1971-76 period, provided by the Scottish Development Department.

The assessment of changes in public consumption of water associated with individual conservation measures can be difficult to make in situations of near simultaneous or overlapping restrictive actions. However, with precise detail paid to the dates of application, often derived from consultation of regional newspapers, the effects of most actions taken during the 1970's could be isolated and quantified, where adequate water consumption data were made available.

The effects of the various actions, whose temporal and geographical incidences are detailed in Section 3, are now considered in turn. The different types of measure are categorised into the following three groups;

- (A) directly enforceable and voluntary consumer economies;
- (B) methods of increasing supplies available to consumers;
- (C) rationing of water supplies.

Categories (A) and (C) include the readily-applied and the more extreme classes respectively, of demand flexibility, whilst category (B) includes all types of supply flexibility. Deficiencies of specific examples referring to the period 1971-76 in Scotland in any of these categories, especially (C), have been overcome by making use of any relevant published information. A summary is provided in Table 4.3, which gives details of the short term supply and demand flexibilities of various reservoir water supply systems in the East of Scotland, based on the events of the period 1971-76. As stated previously, this concentration on one type of supply source is justified by its dominant importance in the provision of water supplies in eastern Scotland, and the severity and extent of the problems involved in their management during the 1970's.

#### 4.4.3 Directly Enforceable and Voluntary Consumer Economies

##### 4.4.3.1 Hosepipe Restrictions

Precise decreases in consumption attributable to this measure are rather difficult to assess, since all such bans are usually accompanied by some degree of publicity aimed at reducing water usage. Appendix 11 gives details for each instance with available data. Some insight into the effects of hosepipe bans alone is given by the two following cases;

(i) a hosepipe ban which was associated with a very low level of publicity in Aberdeen in 1976 achieved a 3.5% saving in consumption;



(ii) the difference in such savings between a hose ban along with a publicity campaign in 1972, and a similar publicity measure minus the ban in 1974 (both in the Edinburgh and Midlothian district) was 5.0 minus 3.2%, ie. 1.8%.

These examples would indicate that savings of around 2 - 3% in normal consumption are achieved by hosepipe prohibitions. This estimate is supported by the findings of Young (1977), who reported a 3% reduction in consumption due to such a ban imposed from February to October in Wessex in 1976. However, this latter figure is associated with that time of the year when use of water, and hence potential savings to be made, via hosepipes, is highest. Therefore, the slightly lower figure of 2% would be a more appropriate average estimate of the savings involved.

Since a hosepipe restriction is a largely standardised measure, then it would seem to be acceptable to extend this general estimate for use in all water authority areas, as is done in Table 4.3.

#### 4.4.3.2 Publicity and Public Relations

The effects of different levels and types of public relations campaigns, which are described in Section 3.3.4.1, on user economy are rather varied. The following details are taken from information summarised in Appendix 11. For the saving in water consumption achieved<sup>ie</sup> by a hosepipe ban and publicity campaign together, a typical figure is 8%. This level occurred in Fife in 1971 and 72, and in Edinburgh



and Midlothian in 1972/3. In the latter area this combination of measures achieved a 10% reduction in consumption in 1959.

In 1973 in Fife, similar measures to those employed in the previous two years with hose bans and public relations campaigns resulted in only a 5.4% reduction in water consumption. A secondary appeal for user economy in the same year succeeded merely in maintaining the existing level of consumption. Two years later, in 1975, the total savings in this area were only 4% of normal consumption. This pattern of events could be attributed to consumer resistance caused by several consecutive years with hose bans and water conservation publicity campaigns.

In the intervening year of 1974 however, amidst the most comprehensive and intensive public relations campaign organised by the Fife and Kinross Water Board, a total maximum saving of 12.8% was achieved. In addition to the usual measures, this campaign involved advertisements on television, house to house leaflet distribution in some areas, large roadside posters, and practice runs with standpipes involving the public. Whilst the latter measure was not primarily intended to be part of a publicity campaign, as it was carried out in restricted areas, it provoked a large public response. The Water Board received several letters expressing concern at this situation, thus indicating an increased level of public awareness of the potential gravity of the water shortage situation.

If say, a 2% reduction in water consumption directly associated with the accompanying hosepipe restrictions is subtracted from all the above figures, the range of effectiveness of public relations campaigns on user economy would involve savings of up to 10.8%, with 6% being a typical level. It should be noted that the maintenance of these levels requires a continuous programme of publicity measures.

The distribution of these savings across the different sectors of consumption are not known. However, Young (1977) reported a 9.9% total saving attributable to public economy in Wessex in 1976, which was split at 4.2% for industrial consumers, and 5.7% for domestic users. In achieving this level of saving, Huntingdon (1977) states that,

"full use was made of the press radio and television".

On the basis of all the values quoted above, it is thought best to use a generalised estimate of 10% as a maximum for all areas. Although no information is available for some regions, that which has been presented above would suggest that savings made in different parts of the country are of a similar order.

The levels of reduction in water consumption above are very low compared with the potential voluntary savings which can be made in this area. For example, Huntingdon (1977), again in Wessex, gives details of two individual domestic cases. In one, a family of four reduced their normal consumption of 114 l per head per day by 40% to 66 l  $\text{hd}^{-1} \text{d}^{-1}$ , and in another, a family of three saved 30% of their previous consumption of 167 l  $\text{hd}^{-1} \text{d}^{-1}$  by taking appropriate conservation measures.



The possible reductions in water consumption in Scotland may well be higher. The S.D.D. (1973a) reported that the average domestic water consumption in Scotland was  $266 \text{ l hd}^{-1} \text{ d}^{-1}$  and in England and Wales only about  $185 \text{ l hd}^{-1} \text{ d}^{-1}$ . This information would suggest that reductions in consumption requested by water boards in potentially severe drought conditions have been quite reasonable and realistic. However, efforts to achieve the 30% and 50% reductions sought by the Fife and Kinross Water Board in 1971, and the South East of Scotland Water Board in 1959 respectively, met with only 8% and 10% savings respectively.

This wide discrepancy between potential and actual savings to be made via an intensive public relations campaign requires some consideration. Since in intensive publicity campaigns, it must be assumed that the vast majority of the population are aware of the appeals of water authorities, there would seem to be two possible main explanations for the apparent non-compliance. The first is that the general public do not trust water authorities, and disbelieve their statements on the severity of water shortages. The only direct evidence of this phenomenon is provided by the public response in Fife in 1974. After three consecutive years of hosepipe restrictions and appeals for economy in water use, the Fife and Kinross Water Board received several letters of complaint, mostly to the effect that they had "cried wolf too soon" as regards these measures. This reaction of distrust only became largely apparent after the three consecutive years of water



restrictions, and therefore could not be used to explain the lack of success of earlier appeals for economy in water use.

A second possible factor responsible for this situation could be considered to be insufficient incentive. For example, since domestic water supplies in particular, are paid for through the local government rating system, no charge is made for the actual quantity consumed. Therefore, there is no direct financial incentive for domestic users to voluntarily reduce their water consumption. There is however, another more obscure incentive which could influence such consumers, ie. the current weather conditions. During the warm and sunny drought of 1976 in England and Wales, Huntingdon (1977) reported the publicity campaigns aimed at reducing water consumption to be "extremely successful." The matter concerning what the public response would have been in dry but dull weather is raised in a paper by Beran and Kitson (1977). It is quite conceivable that the British public, apart from being more aware of potential water shortage, would be more amenable to water authorities' appeals for water conservation, if "in exchange" they had sunny and warm weather. Indeed, such conditions are often used as an explanation for, and an accompaniment to, appeals for water conservation. For example, as recently as 1980, the following headline appeared on the front page of the Edinburgh Evening News of 16.5.80,

"As The Hot Spell Continues - Don't Waste Water".

#### 4.4.4 Methods of Increasing Supplies Available to Consumers

##### 4.4.4.1 Intensified Waste Detection and Prevention

Savings due to this measure can vary widely from region to region, depending on the degree of effort made, and the available room for improvement. In water supply areas such as Edinburgh and Midlothian and that part of Tayside supplied from Loch Lee, where routine or systematic waste detection is carried out, there are limited opportunities for conserving supplies in this field. In fact, actual savings in the above areas of 1 or 2% were rather small compared to the 7.5 - 15.4% levels achieved<sup>ie</sup> by intensive measures in parts of Tayside. These involved house to house inspections in Arbroath, Forfar, Kirriemuir and Blairgowrie. Such reductions in consumption however, may include an element of user economy stimulated by the household presence of water board employees.

Other reported levels of savings resulting from increased waste detection and prevention are of similar proportions. For instance, Young (1977) assessed them at 7% of normal consumption in Wessex in 1976. It should be noted that such levels require continuous effort for their maintenance, as new leaks will continue to require attention.

Potential savings to be made in this sphere are not precisely known, however some indication is given by the fact that Young (1976) estimates that losses through leaks in the U.K. range from 15 - 30% of normal consumption levels.



#### 4.4.4.2 Use of Emergency Supplies

This section covers instances whereby a new or existing resource is utilised to supply an area normally dependent on other means; it does not include cases where existing alternative supply sources are used.

In instances where rural sources supply rural areas, there would seem to be ample scope for flexibility in this area. As was shown in Figs. 3.21 and 3.22, many small sources in Grampian were replaced by new temporary ones. Similarly, so was the supply function of the Fedderate Reservoir in this region in 1972. Another example involves the Watch Water Reservoir serving Berwickshire, whereby an Emergency Order granted in 1973 permitted up to 74% of its normal supply function to be temporarily replaced by a nearby river abstraction.

The two remaining cases in Table 4.3 involving much larger supplies to more populous areas, involved different types of emergency sources. Those brought into action by the South East of Scotland Water Board in 1972 and 73 comprised of three former water supply reservoirs whose function had been superceded by more recently developed larger sources. Jurisdiction over the use of one of them has remained with the water board, However, in order to utilise the other two, the water board had to obtain conditional clearance by way of an Emergency Order.

The effort required by the Fife and Kinross Water Board to obtain and secure emergency supplies was much greater. A feasibility study on the use of boreholes to



augment supplies led to the permanent provision of 10% of normal requirements. Another, though temporary 10%, was purchased from the then Mid Scotland Water Board over 24 months of the period 1973 - 75. This required the construction of two new pipelines, one across the Firth of Forth at Kincardine.

#### 4.4.4.3 Reduced Reservoir Compensation Flows

Just as the extent of reductions in compensation flows varied greatly (30 - 100% for individual reservoirs in Table 3.9), so too do the range of corresponding savings made in relation to normal supply requirements. As Table 4.3 reveals, these vary from less than 5% for the Edinburgh and Midlothian supply area, where all of the major supply reservoirs' compensation flow remained unaltered; to 250% for the area supplied by Loch Lee, where normal compensation flow ( $29.5 \text{ Ml d}^{-1}$ ) greatly exceeded the draw off for public supply of  $7.3 \text{ Ml d}^{-1}$  in 1971.

Indeed, these extreme examples reflect the general pattern, in that proportionately low savings were achieved for supply systems serving the more populous urbanised areas such as Fife and Lothian, compared to those rural areas in Tayside. From the information displayed in Table 3.9, it is apparent that the vast differences are not wholly attributable to smaller percentage reductions in compensation flows in reservoirs supplying Fife and Lothian. What is of more relevance is the proportion of outflow from each reservoir which is compensation water, rather than that for

public consumption. For example, in the following three impounding reservoirs in Tayside, Loch Benachally, Den of Ogil and Loch Lee, compensation flow exceeds the quantity supplied to consumers. Contrastingly in Fife, compensation water comprises only around 25% of the total demand on reservoired sources.

Other features encompassing a wide range of variation are the time, effort and finance required by water authorities to enforce their proposed reductions in reservoir compensation flow. In most cases, Emergency Orders had to be applied for and granted. This is a relatively straightforward procedure, but in instances where formal objections are lodged with the Secretary of State, delays and difficulties can occur. For example, objections raised by the North Esk District Fishery Board to the reduction of compensation flow from Loch Lee in Tayside in 1976, resulted in one month's delay in the implementation of an Emergency Order. In addition, the proposed 80% reduction in compensation flow was altered to a compromise level of 62%.

A condition of all such reductions, both voluntary and statutory, is that water authorities must consider and meet claims for damages and loss of revenue presented by affected parties. Details are of course confidential, but information made available, and displayed in Table 4.2, provides examples occurring over the period 1973-75, and gives an insight into the costs involved.

The lowest three individual costs are those meeting the claims of District Fishery Boards, whilst the largest

was paid in compensation for reduced levels of power generation from the river downstream of the affected reservoir. Total quantities of money involved were relatively low, with all known claims in any one year being in the range £100 - £1,000.

TABLE 4.2 :    Sample Compensation Costs Made to Claimants  
                  Affected by Reduced Reservoir Compensation Flows.

Compensation Flow Reduction (MI d <sup>-1</sup> )	Cost	
	£ per day	£ per MI
4.3	6.26 } 0.80 } 7.06	1.46 } 0.19 } 1.65
3.4	2.24	0.66
7.4	4.92	0.66

4.4.5    Rationing of Water Supplies

The more severe methods of reducing consumption which were either not experienced or not sufficiently well recorded during the 1971-76 drought in Scotland include;

- (1)    decreasing water pressure in mains;
- (2)    rationing the temporal availability of water;
- (3)    use of stand pipes.

However, some estimates of the percentage savings in consumption involved can be obtained from other sources. The three types of action above are now considered in turn.



#### 4.4.5.1 Decreasing Water Pressure in Mains

Young (1977) reports that in 1976, savings on normal consumption in Wessex due to pressure reductions were between 4.5 and 15%, and that those attributable to "stop tap throttling" lay in the range 5 - 15%. The applicability and effectiveness of such measures will vary greatly from area to area, depending on local water supply characteristics. Any savings due to this measure would be limited to water uses where the duration of consumption, rather than the volume, was the decisive factor. For example, under such circumstances, it would be more likely for someone<sup>n</sup> using a shower to use proportionately less than normal quantities of water, than someone having a bath, which involves storage.

#### 4.4.5.2 Rationing The Temporal Availability of Water

The discontinuation of supplies between the hours of 7p.m. and 7a.m. on a rota basis in 1959 in Edinburgh saved 21% of potential consumption in affected areas. A similar twelve-hour cut-off achieved<sup>ie</sup> a saving of 25% on normal domestic consumption in Wales in 1976 (Lillicrap, 1977), whereas Young (1977) indicates that 50% savings could be achieved by 17-hour cuts.

#### 4.4.5.3 Use of Stand Pipes

Few recorded examples of the use of stand pipes exist. In one case occurring in 1976 in the south-west of England, Young (1977) reports savings of 45 - 50% in individual areas.

The necessary areal selectivity of the application of this measure (to avoid affecting essential services such as hospitals) however, meant that its overall contribution to saving on normal consumption was 33%.

It should be noted here that the latter two measures should be regarded as alternatives, as they could not successfully be implemented simultaneously. Young (1977) gives detailed consideration to the desirability and applicability of these rationing methods, and suggests that generally rota cuts are more acceptable and practical, leaving the use of stand pipes suited only to the "extreme situation".

#### 4.4.6 Applicability of the Short Term Flexibilities of Water Supply and Demand

The ranges of flexibility of supply and demand for most reservoir supply systems is surprisingly high, especially for those where considerable advantage can be taken of flexibility of supply, ie. category (B) in Table 4.3. However, as the applicability of the various measures are rather selectively appropriate, water authorities with few options of this type can have a somewhat limited range of drought management actions available. In addition, measures such as emergency supply provision, and to a lesser extent, increased waste prevention, can involve permanent adjustments to supply capabilities and therefore could reduce the flexibility of supply available for future drought situations.

TABLE 4.3 : The Flexibility (Measured as a %) of Normal System Supplies from Reservoirs  
Sources in the East of Scotland : Based on the Events of 1971-76 and Some  
Generalised Figures.

Category	Reservoir Supply area Water Board	Watch Water Berwickshire South East	Various Edinburgh+ Midlothian South East	Various Fife Fife and Kinross	L.Benachally Blairgowrie East	Den of Ogil Forfar East	Glenogil Arbroath East	Loch Lee N.E. Tayside East	Fedderate Fraserburgh North East	Comments
	Type of measure									
A	Hosepipe ban Publicity	2 10	2 10	2 10	2 10	2 10	2 10	2 10	2 10	Standard maximum values
B	Waste reduction Emergency supplies Reduced compensation	74 18.5	(2) 11 4.7	(1) 20 18.5	15.4 50-260	8.5 90-180	10 29-57	250	25-100	
C	Reduced pressure Rota cuts Standpipes		21 (in 1959)							est. average of 20 33 (Young, 1977)
Totals										
Total for A		12	12	12	12	12	12	12	12	
Total for B		92.5	17.7	39.5	65-275	99-188	39-67	250	25-100	
Total for A+B		104.5	29.7	51.5	77-287	111-200	51-79	262	37-112	
A+B+Rota cuts		124.5	49.7	71.5	97-307	131-220	71-99	282	57-132	
A+B+Standpipes		137.5	62.7	84.5	110-320	144-233	84-112	295	70-145	



For example, only half of Fife's 20% saving due to use of emergency sources can be regarded as temporary, whilst the other half involving borehole developments are of a permanent nature. Similarly, the savings of up to 15.4% attributable to intensive waste prevention in Tayside must be regarded as at least partially permanent.

These considerations are particularly relevant in relation to the nature of flexibility of demand, which in some cases of limited supply flexibility, eg. Edinburgh and Midlothian and Fife, may have to be heavily relied on. Most notable is the vast difference in the possibly sequential statutory measures of firstly a hosepipe ban followed by rota cuts. These actions achieve<sup>ie</sup> around 2 and 20% savings respectively, which represents a rather drastic step in the severity of water conservation measures. Perhaps a gradual increase in the duration of rota cuts would offer a more acceptably progressive procedure, but Young (1977), in considering the operational efforts and problems involved, concludes that short duration cuts may not be practical.

This apparent inadequacy of flexibility in this area of reducing public consumption is given further supportive evidence from the actions of one particular Water Board detailed in Section 3.3.4.1. These involved the imposition of restrictions on water uses which were outwith the available statutory powers. Such powers, and indeed many others were in fact provided for by the Drought Act of 1976, which applied to England and Wales.

This Act, which was hurriedly passed through parliament in August 1976 (Samuels, 1977), was as Musgrave (1977) reports, intended to provide "powers that would allow restrictions to be applied progressively as the situation worsened", with particular emphasis on the prohibition or limiting of "inessential" uses of water. To this end, in addition to the provisions of the Act of 1958, Section 1 of the 1976 Act allowed Emergency Orders to be granted which gave the authority to prohibit or limit the use of water for any purpose, prescribed by the Secretary of State in a "direction" given to water authorities. This "drought direction" listed the following uses:

(a) the watering, by hosepipe, sprinkler or other apparatus, of parks, ornamental gardens, lawns, recreation grounds, sports grounds, playing fields, golf courses or racecourses, whether publicly or privately owned;

(b) the filling, whether wholly or partially, of privately owned swimming pools other than fish ponds;

(c) the operation of mechanical car washers, whether automatic or not;

(d) the washing of road vehicles for any reason other than safety or hygiene;

(e) the cleaning of the exterior of buildings;

(f) the operation of ornamental fountains or cascades, including any where water is recycled;

(g) the operation, in relation to any building or other premises, of any system which flushes automatically during any period when the premises are wholly or substantially unoccupied.



Furthermore, Section 2 of this Act included a provision, by way of an Emergency Order, enabling water authorities to prohibit or limit the use of water for such purposes as they thought fit.

The preparation of the bill for the 1976 Act revealed a somewhat anomalous situation. Agnew, in Musgrave (1977) reports that "very careful consideration was given to whether the powers should extend to Scotland", and indeed they did not. However, no move towards making such provisions appears to have been made concerning the much more serious water shortages in 1972 and 73, when indeed, judging by the illegal actions of one particular Water Board, such powers might well have been welcomed by water authorities in Scotland.

#### 4.4.7 Organisation of Measures Towards a Policy

Now that the ranges of flexibilities of supply and demand of water from public supply reservoirs available during drought conditions have been assessed, the problem remains as to their application. This involves the sequence and timing of successive actions.

The most obvious and useful pattern of such events, as noted by Crann (1977) and Young (1977), is that of a sequence of progressively more severe restrictions on the use of existing sources as they continue to dwindle. This systematic approach was the one apparent in the affected parts of Scotland in the period 1971-76. For instance, it



has been indicated in the foregoing pages that the occurrence and duration of, hosepipe restriction, reductions in reservoir compensation water, and the use of standpipes, decreased in that order, whilst their individual proportionate contributions to the conservation of supplies increased.

It is, however, the timing of the imposition of such actions that would seem to be the most problematic area. As Crann (1977) indicates, the drought manager has to balance the conflicting interests of;

(i) maintaining supplies at a tolerable minimum for as long as the drought lasts;

and (ii) avoiding the unnecessarily early imposition of restrictions and the resulting public disapproval and possible lack of future cooperation.

Crann goes on to consider that the mistiming of restrictions can have, "a very substantial reduction in their effectiveness", and he stresses further the importance of maintaining public confidence in an authority's competence in drought management. It should be noted here that this contention cannot be applied to water supply systems involving negligible storage. In such circumstances, the level of restrictions in usage are simply determined by what is available at any given time.

The example referred to earlier, in Section 4.4.3.1, concerning hosepipe restrictions in Fife would perhaps seem to bear out Crann's statements. The facts that;

(i) savings due to such bans and publicity campaigns in

the years 1971 to 74 ranged from 8 - 12%, but dropped to only 4% in 1975 (details in Appendix 11); and that (ii) some adverse public reaction was encountered at the end of the 1974 campaign (detailed in Section 4.3.3.2); would tend to indicate some public disillusionment with the actions of the Fife and Kinross Water Board. Therefore, it would be prudent to make an assessment of the timing of hosepipe bans and the associated publicity campaigns in Fife over the affected period.

TABLE 4.4 : Quantities of Water in Store During Hosepipe Restrictions Imposed in Fife and Kinross from 1971 to 1975.

Date of imposition	% of maximum storage	Intervening storage		Date of relaxation	% of maximum storage
		Lowest (% of max.)	highest (% of max.)		
5.10.71	44	44	86	12.1.72	86
3.11.72	41	36	86	7.1.74	76
1.7.74	64	49	60	14.10.74	57
4.9.75	47	44	69	10.10.75	69

From Table 4.4, two particularly interesting facts can be identified, as follows;

(i) the measures taken on 3.11.72 continued through to 7.1.74 (a period of 14 months), despite the fact that the level of storage (86%) which coincided with the removal of the previous ban on 12.1.72, had been attained in February and March 1973;

(ii) the hosepipe ban and publicity campaign of 1974



began when available storage was at 64% of total capacity. These actions ceased when storage was in fact lower, at 57% capacity on 14.10.74. In all other cases, hose bans were relaxed only when storage was considerably greater than that on their imposition.

It is conceivable that such inconsistencies in the application of hosepipe restrictions could have caused some public resentment of the actions of the Fife and Kinross Water Board. When approached as to their policy regarding a contingency plan for the management of their water resources in drought conditions, Fife Regional Council (the new administrative body since 1975) declined to offer any information on the matter. However, Lothian Regional Council did make available their drought management plan, which was utilised from 1972 to 1974. A critical appraisal of this plan now follows.

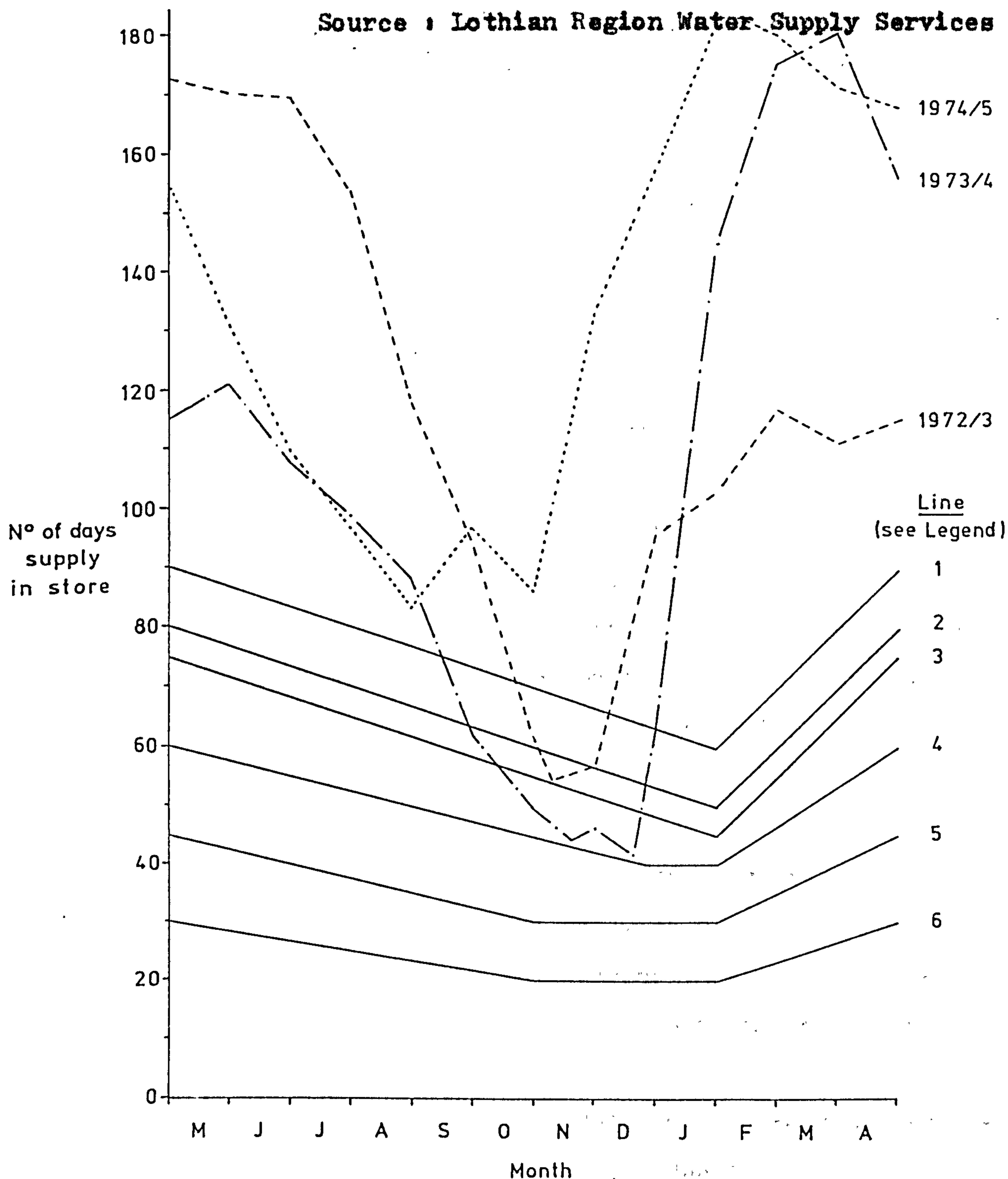
#### 4.4.8 Assessment of a Drought Management Plan Implemented in the 1970's

The drought management contingency plan adopted by the Edinburgh and Midlothian division of the Lothian Region Council Water Services is shown in Fig. 4.3. This procedure consists of a phased programme of conservation measures which was originally used to manage the drought of 1959 affecting the area. In that year, action was taken as far as step (5) ie. rota cuts, whereas in 1973 reservoir storage was such that step (4) was just avoided, as Fig. 4.3. indicates.



**FIGURE 4.3 : The Drought Management Plan for the Edinburgh and Midlothian Supply Area, and the Number of Days Supply in Store During the Period 1972/3 - 1974/5**

**Source : Lothian Region Water Supply Services**



**Legend**

- |            |     |   |
|------------|-----|---|
| Below line | (1) | Warn consumers of situation and ask for economies in use of water.  |
| "          | (2) | Increase publicity, restrict use of hosepipes in the terms of the Water (Scotland) Act 1946 Sec. 59.  |
| "          | (3) | Continue publicity. Apply to Secretary of State for orders to reduce compensation water (Water Act 1958, Section 1).                            |
| "          | (4) | Intensify Publicity and reduce pressure in mains where possible (Apply for order to allow for the use of standpipes (Water Act 1958 Section 2). |
| "          | (5) | Institute rationing by turning off mains at night etc.  |
| "          | (6) | Institute use of standpipes.  |

This type of drought management policy consists of a form of rationing whose rationale is based entirely on what storage is available at given points in time. For example, it does not consider probabilities concerning either;

(i) the events leading up to critically low reservoir levels;

or (ii) the prospects for reservoir storage and water supply in the near future.

It could be argued that the seasonal adjustments made for each progressive action introduce some notion of probability, as regards the seasonal nature of water storage levels and drought. The toleration of given low storage levels is gradually increased from May to January, whereafter it decreases to its minimum at the end of April. Another similar method of assessing the desired reductions in reservoir outflow, and hence the required savings in consumption, is that used by the Wessex Water Authority (Huntingdon, 1977). This system of "reservoir control curves" follows the same pattern, with the exception that the maximum toleration of low reservoir levels occurs at the end of November, rather than in January, as in the one for Edinburgh and Midlothian.

Such drought management models imply important assumptions. In the case of the latter, a decline in storage is deemed possible from May to January, and the following recharge period is expected to begin by February. This situation occurs in the vast majority of years, and the pattern of events in the 1970's supports this assumption,

as well as the inherent contention that the later (up to January) the minimum storage occurs, the lower it can be, as Fig. 4.3 indicates.

However, in the drought of 1959, when the pre-drought system adequacy ratio for Edinburgh and Midlothian was the same as in 1972, the minimum storage level corresponding to 35 days supply occurred relatively early in the year, ie. in mid-October. This example, and the recollection that one of the necessities for "drought" as defined in this thesis ie. "an abnormal spell of weather", render the use of relationships between minimum tolerable storage levels in reservoirs and the time of year somewhat limited. This is especially so if this "abnormality" is regarded, at least partially, as a temporal one, eg. the prolongment, cutting short, or even complete absence of a given hydrologic season; rather than one measured in terms of durations from normal over well-defined seasonal periods. An example of this view of abnormality is given in Section 3.2.3, Fig. 3.2, where it can be seen that the normal winter season characteristics of run-off at Luffness on the Peffer Burn West in East Lothian failed to occur in 1972/3 and 1973/4.

#### 4.5 IMPLICATIONS OF THE MAJOR ISSUES RAISED IN SECTION 4.

The foregoing pages have identified and outlined the various topics involved in the planning and management of



reservoired water supply resources which require further attention in relation to the subject of drought. These are summarised below, firstly for the field of planning, for which the following matters are of greatest relevance.

The applicability of calculating reliable yields of reservoirs on the basis of three-year minimum rainfall totals has been questioned. A more appropriate technique would involve actual run-off data, and a time base considerably less than three years. Also, there is a need for more precise estimates of probabilities of failure of water supply reservoirs. As regards a suitable measure of reliability, the Central Water Planning Unit (1977) suggest that, "a more meaningful definition might be to express the reliability of the supply in terms of the restrictions which would have to be imposed, calculated for a long period of say, 100 years".

The need for optimal failure probabilities to be assessed raises the matter as to whether the consumer should be consulted in an attempt to find the most acceptable balance of supply and demand of water, over both the long and short terms, the latter referring to periods of actual or threatened drought.

Successful drought management of water supply reservoirs can be very dependent on public support and cooperation. As Young (1977) recognises, there is therefore a need not only to keep consumers fully informed, but to administer water conservation measures with commonsense and understanding. For the fulfillment of this, and all the above conditions, a rational policy of implementation of various

short term measures to increase supply capability, and also to decrease demand in drought conditions, is required. Ideally, different types of policy could be derived and tested on public opinion, in accordance with the points raised above.

It is with all the foregoing matters in mind, that the following section considers an alternative system of drought management and reliable yield estimation for water supply reservoirs.

SECTION 5

A SYSTEM FOR OPTIMAL YIELD ESTIMATION AND DROUGHT  
MANAGEMENT OF RESERVOIRED WATER  
SUPPLY SYSTEMS



## 5.1 INTRODUCTION

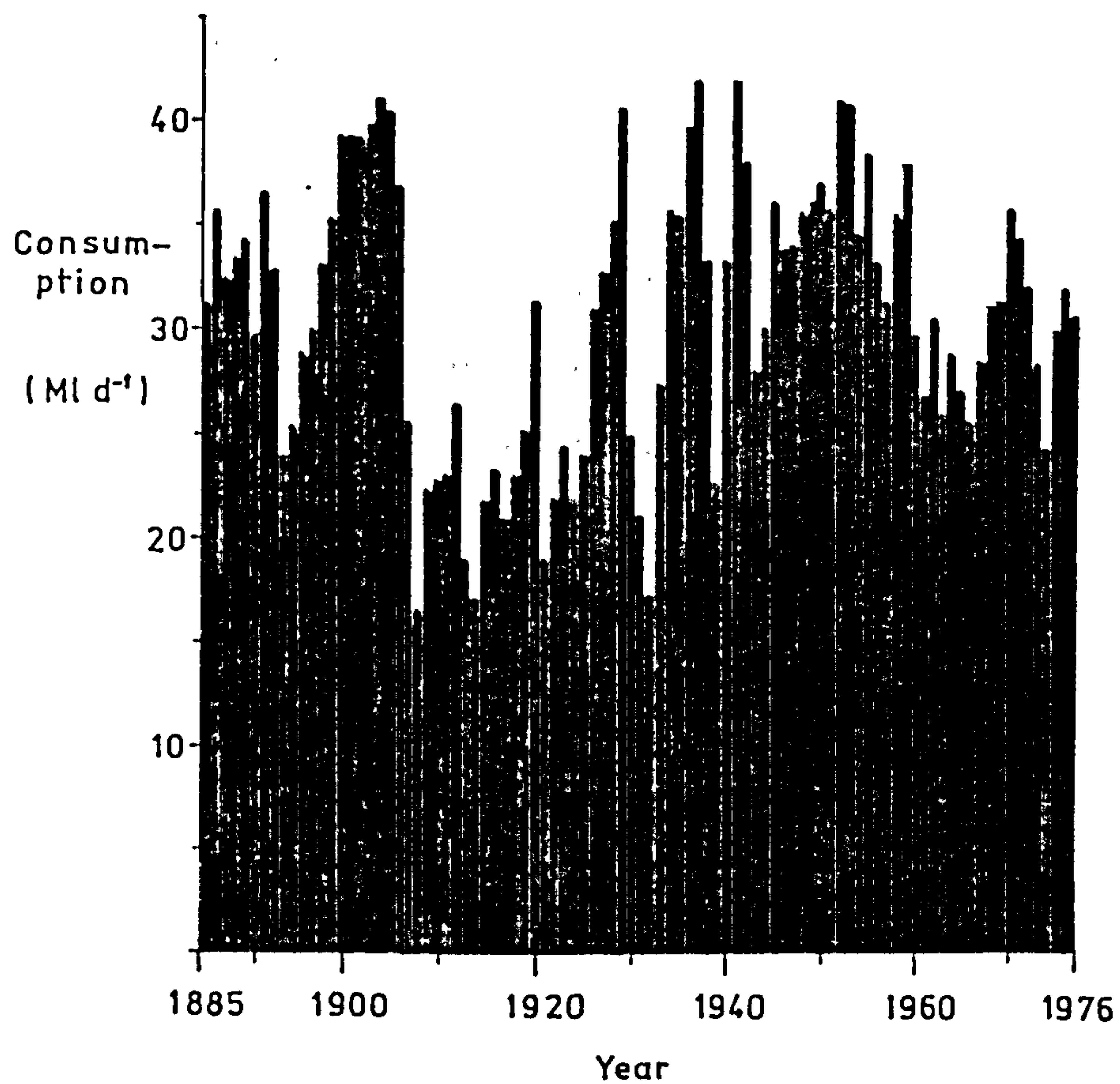
In response to the matters raised in the previous pages, this section attempts to formulate an alternative basis for the planning and management of impounding reservoirs. Since the purpose of this exercise is to formulate and illustrate a new methodology, then it is considered most appropriate that a detailed case study should be presented for one individual reservoir supply system.

## 5.2 THE STUDY RESERVOIR

Gladhouse Reservoir, in Midlothian, is especially suitable because of the 92 years of records which, as described in Section 2.6.2, allow the derivation of a long run-off series. In addition, some aspects of the historical usage of this reservoir would indicate its particular applicability to such a study.

The reservoir's pattern of usage over the 92-year period of record shows considerable variation, as Fig. 5.1 indicates. Annual rates of consumption have ranged from 15 to 40 Ml d<sup>-1</sup> since 1885. Some of this variation can be explained by the development of new resources, and a subsequent re-appointing of supply functions. For example, the introduction of the Talla Reservoir in 1905 effectively halved the rate of consumption from Gladhouse Reservoir for several

**FIGURE 5.1 : Annual Average Daily Consumption from Gladhouse Reservoir for the Years 1885 to 1976**



years. The initiation of other periods of one year or more of reduced consumption tends to correspond, to some degree, to occasions when reservoir storage has dropped to a particularly low level. Instances of this occurrence coinciding with, and possibly having an influence on reservoir draw-off rates happened in the years, 1929, 1937, 1959 and 1969, when minimum storage levels of less than 20% of total capacity were attained.

Indeed, in the years of 1959 and 1972/3, the quantity of water in store reached depletions of only 10% of maximum storage. On the latter occasion, a pipeline was laid from an alternative supply source in East Lothian to replace temporarily, some of the supply functions of Gladhouse Reservoir.

As a result of these events, doubts concerning the reliable supply capability of the reservoir were raised sufficiently to instigate a re-assessment of the official "reliable yield". In 1973, the original figure of  $42.3 \text{ Ml d}^{-1}$  was reduced substantially to one of  $34.6 \text{ Ml d}^{-1}$  (Lothian Region Water Supply Services, 1980).

### 5.3 A PRIMARY ESTIMATION OF RELIABLE YIELD USING RUN-OFF DATA

#### 5.3.1 Introduction to the Basic Technique

The basis of the method to be used is that first introduced by Moran (1954 and 1959), and subsequently reviewed by Harris (1965) and Lloyd (1963 and 1970). This procedure provides a technique for describing the probability



distribution of reservoir contents, with particular regard paid to the probability of the incidence of zero contents, ie. total supply failure.

As Harris indicates, since it is not possible to use continuous distributions of reservoir contents, discrete variables have to be employed. Accordingly, the contents are classified by a number of equal-size "states". Then, for a given "initial state", the probability of arriving in any given "final state" is calculated. In this particular case, the movement between states is best suited to the two-season model as described by Lloyd and Odoom (1964). Reservoir storage records reveal that there are two distinctive annual seasons, when;

(i) the reservoir outflow rate exceeds the inflow rate; and (ii) the reservoir inflow rate exceeds the outflow rate.

The former corresponds to a period of depletion of storage, and the latter to a subsequent accretion. However, Moran's adoption of definite seasonal periods is, as Harris noted, not appropriate in Britain. A "variable season model", as recommended by Cole et al (1970) would seem to provide a more useful approach, and is the one employed in this study.

All calculations of mathematical and statistical natures in this case study were mostly carried out using the ICL 2970 computer facility provided by the Edinburgh Regional Computing Centre.

As regards actual details of the procedures involved, Harris presents a comprehensive illustrative example, the

main points of which are summarised here. The first step is to obtain a series of "Net Additions to Storage" (or NAS, as referred to by most authors) for both the depletion and recharge seasons. The former are generally negative (NASN) and the latter positive (NASP). In this case the seasonal divides were taken to be;

(i) the date of summer minimum contents;  
and (ii) the date of winter maximum contents, or if maximum capacity was reached, the last day of its occurrence.

By computation involving inter-seasonal changes in storage, and the various outflows (compensation water, overflow and public water supply) between specific dates as determined above, NASN and NASP series were derived.

Since consumption has varied considerably over the 92-year period, the recorded rates of consumption during the individual NASN and NASP periods were adjusted to obtain homogeneous series corresponding to standardised consumption rates of 27.3, 31.8, 34.6, 37.7 and 42.3  $\text{Ml d}^{-1}$ . These levels of supply include the two official estimates of reliable yield mentioned earlier, along with some typical rates of draw-off occurring over the 92-year period.

This procedure of homogenisation can lead to some distortion of the standardised NASN and NASP series, in that the actual date of changeover between seasons will be dependent on the original rate of consumption. Consequently, the adjustment of these observed values to normalised ones can cause errors in the estimation of the timing of, and



values obtained for NASN and NASP events. In the vast majority of cases, the changeover between these two seasonal events is typified by such a rapid change in inflow rate, that the errors above typically correspond to less than  $\pm 2$  days in the measurement of each season. Consideration of the fact that these seasonal events are of an average duration of 6 months, the corresponding errors of the order of 1% are negligible compared to errors from other sources which are described later in this section, and have been ignored.

### 5.3.2 NASN and NASP Probability Distributions

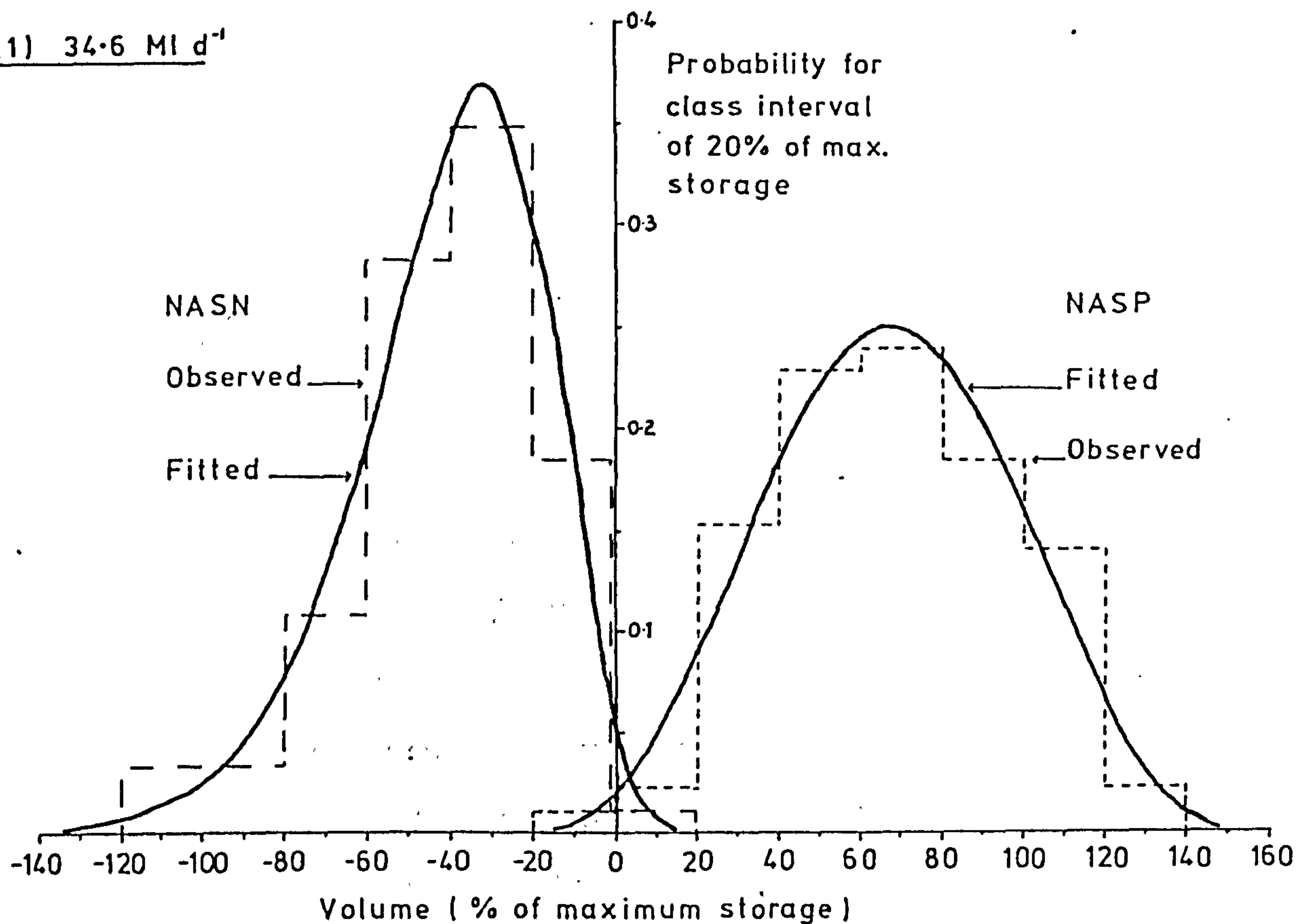
The next stage involves the fitting of standard statistical distributions to the NASN and NASP series. This procedure can be a rather contentious issue, and Gould (1961) opted for the alternative method of "probability routing" at this point in a similar study. Other workers have utilised various skew and non-skew statistical distributions, including the Normal or Gaussian (Lloyd and Harris), the Log-normal (Harris) and the Gamma or Pearson Type III (Cole and Lloyd).

Histograms representing the NASN and NASP series derived for Gladhouse Reservoir are shown, along with their best-fit curves, for two separate rates of constant consumption (or normal system supply) of 34.6 and 42.3  $\text{Ml d}^{-1}$ , in Fig. 5.2. All derived NASP distributions, which tend to be symmetrical around modal values, are best fitted by a Pearson Type III curve rather than the obvious alternative of a Gaussian

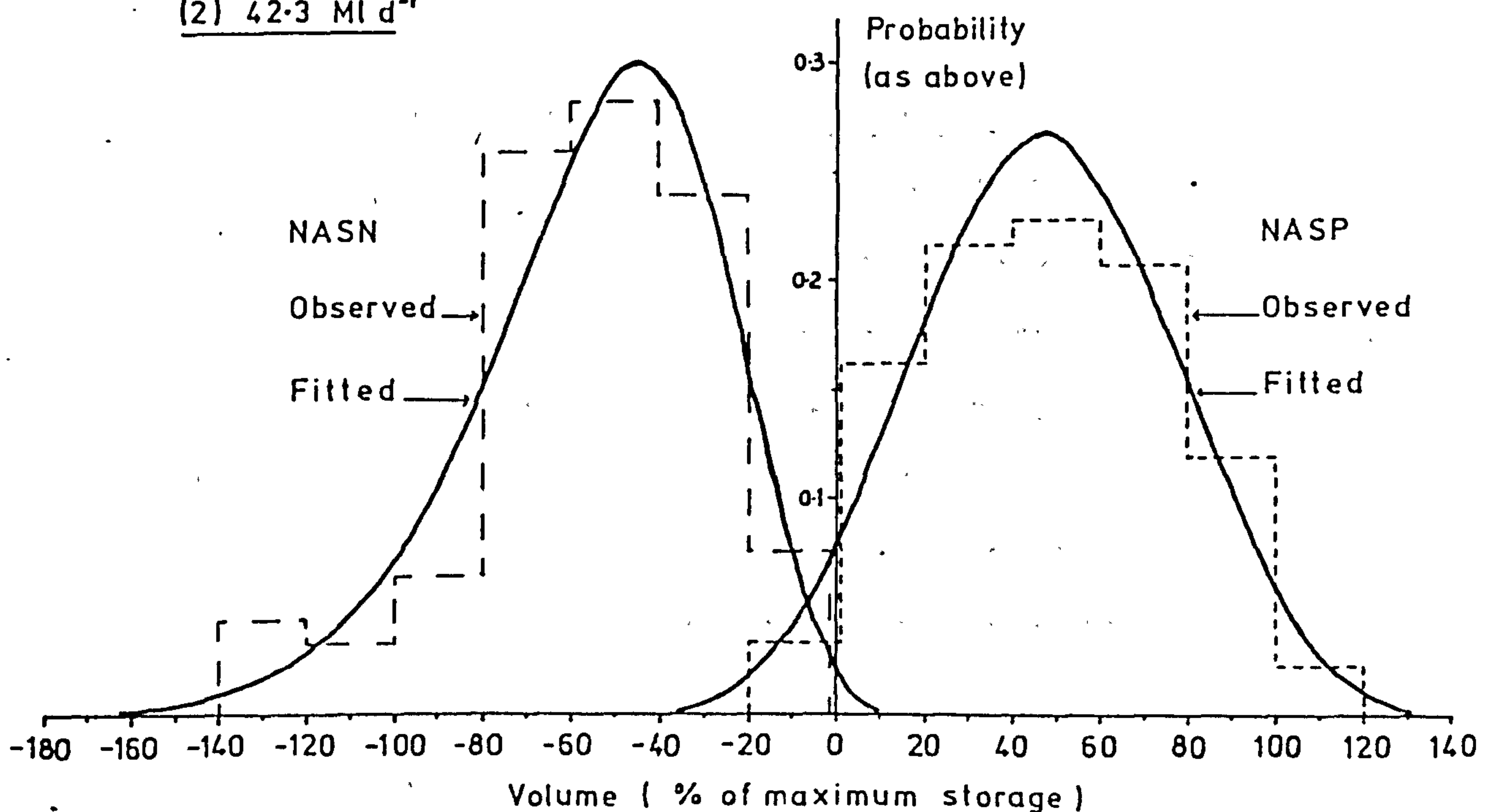


**FIGURE 5.2: Observed and Fitted Probability Distributions for NASN and NASP Series at Gladhouse Reservoir for Normal System Supply Rates of:**

(1) 34.6 MI d<sup>-1</sup>



(2) 42.3 MI d<sup>-1</sup>



Distribution. In the case of NASN distributions, the most suitable curves are always of the Pearson Type III category. The estimation of the various fitting parameters for the five NASP and NASN series was done by the methods introduced by Pearson (1895) and re-appraised by Kelley (1924).

As the examples on Fig. 5.2 indicate, at higher rates of normal system supply (NSS), both NASN and NASP curves are displaced and "stretched" towards lower values. The horizontal scale on these diagrams has been chosen to correspond with the discrete units of NASN and NASP to be employed. These units correspond to 10% of the maximum storage capacity, ie. 813.3 ML.

The relevant areas under the fitted curves can be used to ascribe discrete probabilities to each of these units of NASN and NASP, thus dividing each distribution into about 15 individual probability values. These probabilities are then assigned to given changes in storage for both NASN and NASP events.

### 5.3.3 The Arrangement of Reservoir Storage States

In accordance with the NASN and NASP distributions, the storage "states" are spaced at intervals corresponding to 10% of maximum capacity, as is illustrated in Fig. 5.3, for NASN season <sup>itions</sup> ~~transformations~~. This procedure provides for 10 states down to the zero contents level represented by state "0", in much the same manner as that of Harris (1965) and Cole et al (1970). However, an important additional

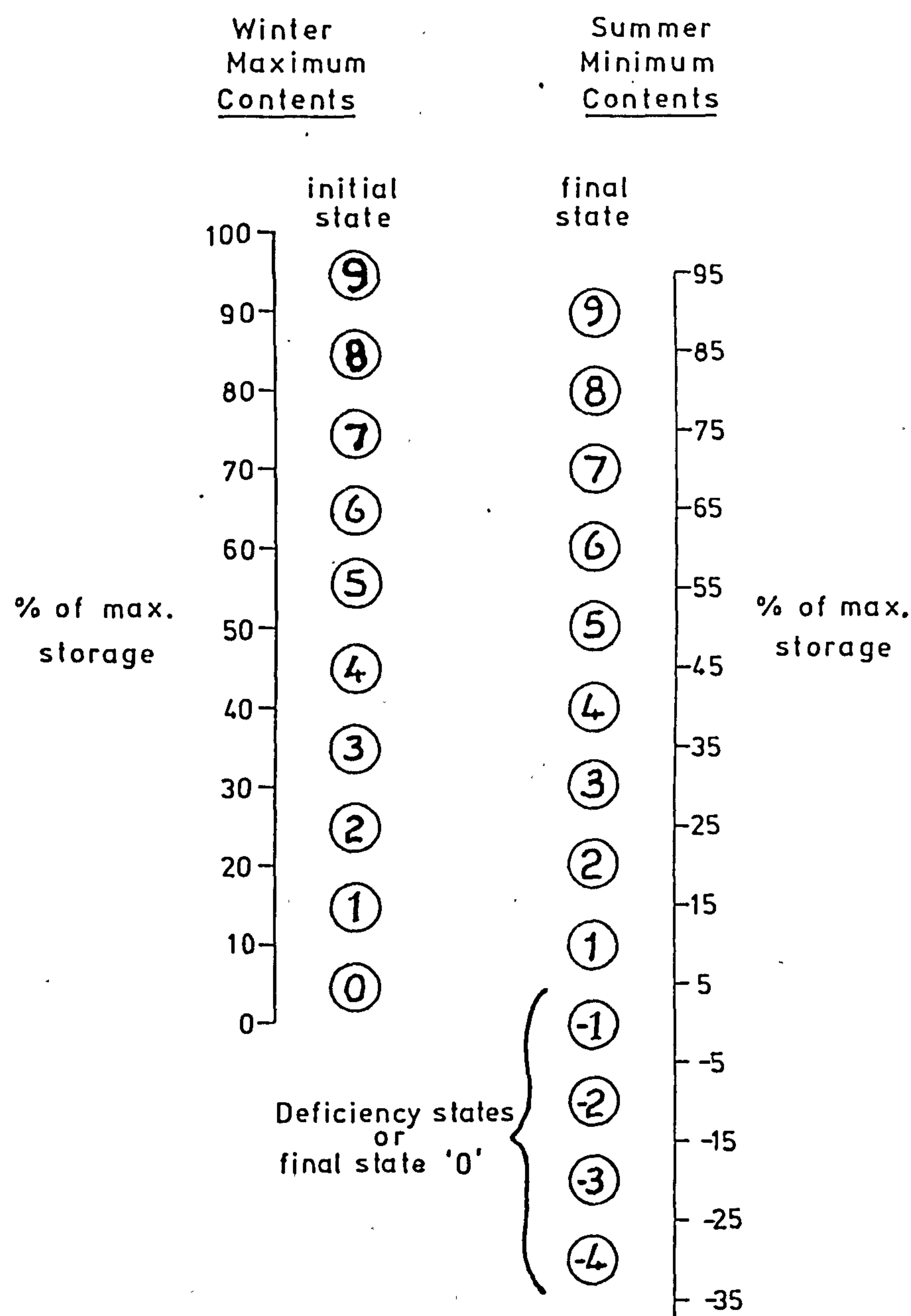
feature has been included, ie. the extension of these states below the positive values to allow an examination of different "states of deficiency". In effect, this involves the subdivision of the "0" state into the standard units as before, and has only been done for the final series of states following NASN events, after which measurable probabilities of emptiness occur. Such a refinement provides not only for the incidence of failure or emptiness of the reservoir (the concern of all authors up to and including Pegram (1980) on the subject), but also for an assessment of different potential levels of failure, which follows in Section 5.4.

The "staggered" arrangement of initial and final states, which is illustrated in Fig. 5.3 for NASN events, as employed by Harris (1965) deserves explanation. Since the progression from one of these states to the other (ie. NASN or NASP) is measured in ranges corresponding to 10% of maximum <sup>storage</sup> ~~capacity~~, this allows for the transference from any mid-value in an initial state to a precisely defined range of storage defined by the final state, no matter where in its range a given NASN or NASP event falls.

Whenever a particular storage state is referred to, this has an approximated discrete value corresponding to the mid-point of its range. Since this is 10% of maximum reservoir storage, the use of states to describe reservoir contents means that all stated volumes have a maximum possible range of  $\pm 5\%$  of maximum capacity, ie  $\pm 407$  Ml.



FIGURE 5.3 : The Arrangement of Storage States for NASN Events



#### 5.3.4 Matrix Formulation

The two objectives involved here are;

(i) to assign the probabilities associated with change from any given state to any other, for both NASN and NASP events;

and (ii) to estimate the "steady-state" probabilities for each set level of storage for the two seasonal extremes (or final states, after both NASN and NASP transitions). Firstly, the series of probabilities derived for discrete NASN and NASP values can be used to represent the probabilities of progression from one seasonal extreme to another. These are best shown in tabulated form or matrices. Figs. 5.4 (1) and 5.4 (2) provide examples for both NASP and NASN seasons respectively, for a normal system supply rate of  $34.6 \text{ Ml d}^{-1}$ , for states 0 to 9. In Fig. 5.4 (3), the NASN matrix from Fig. 5.4 (2) is extended in the manner indicated earlier, to include a further 16 final NASN deficiency states, and their associated probabilities. The sum of these probabilities for each column, or initial NASN state, represents the total probability of failure, ie. state 0, which is shown as the last row in Fig. 5.4 (3).

Matrices taking the form and values of the two initial parts of Fig. 5.4, when multiplied together give the two yearly transition matrices. One corresponds to the seasonal maximum contents at the end of NASP periods and is given by  $[\text{NASN}] \times [\text{NASP}]$ , and the other pertaining to the minimum contents at the end of NASN events is derived from the converse matrix multiplication.

FIGURE 5.4 : Probability Matrices for a Normal System  
Supply of 34.6 Ml d<sup>-1</sup> for:

(1) NASP Events

Final state	Initial state									
	0	1	2	3	4	5	6	7	8	9
9	0.2352	0.3451	0.4665	0.5917	0.7088	0.8107	0.8912	0.9477	0.9811	0.9959
8	0.1099	0.1214	0.1252	0.1171	0.1019	0.0805	0.0565	0.0334	0.0151	0.0041
7	0.1214	0.1252	0.1171	0.1019	0.0805	0.0565	0.0334	0.0151	0.0041	0.0000
6	0.1252	0.1171	0.1019	0.0805	0.0565	0.0334	0.0151	0.0041	0.0000	0.0000
5	0.1171	0.1019	0.0805	0.0565	0.0334	0.0151	0.0041	0.0000	0.0000	0.0000
4	0.1019	0.0805	0.0565	0.0334	0.0151	0.0041	0.0000	0.0000	0.0000	0.0000
3	0.0805	0.0565	0.0334	0.0151	0.0041	0.0000	0.0000	0.0000	0.0000	0.0000
2	0.0565	0.0334	0.0151	0.0041	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
1	0.0334	0.0151	0.0041	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0	0.0192	0.0041	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

(2) NASN Events

Final state	Initial state									
	0	1	2	3	4	5	6	7	8	9
9	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0115	0.0678
8	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0114	0.0563	0.1239
7	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0114	0.0563	0.1239	0.1714
6	0.0000	0.0000	0.0000	0.0000	0.0001	0.0114	0.0563	0.1239	0.1714	0.1824
5	0.0000	0.0000	0.0000	0.0001	0.0114	0.0563	0.1239	0.1714	0.1824	0.1527
4	0.0000	0.0000	0.0001	0.0114	0.0563	0.1239	0.1714	0.1824	0.1527	0.1145
3	0.0000	0.0001	0.0114	0.0563	0.1239	0.1714	0.1824	0.1527	0.1145	0.0775
2	0.0001	0.0114	0.0563	0.1239	0.1714	0.1824	0.1527	0.1145	0.0775	0.0486
1	0.0114	0.0563	0.1239	0.1714	0.1824	0.1527	0.1145	0.0775	0.0486	0.0286
0	0.9885	0.9322	0.8083	0.6369	0.4545	0.3018	0.1873	0.1098	0.0612	0.0326

(3) Extended NASN Events

Final state	Initial state									
	0	1	2	3	4	5	6	7	8	9
9	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0115	0.0678
8	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0114	0.0563	0.1239
7	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0114	0.0563	0.1239	0.1714
6	0.0000	0.0000	0.0000	0.0000	0.0001	0.0114	0.0563	0.1239	0.1714	0.1824
5	0.0000	0.0000	0.0000	0.0001	0.0114	0.0563	0.1239	0.1714	0.1824	0.1527
4	0.0000	0.0000	0.0001	0.0114	0.0563	0.1239	0.1714	0.1824	0.1527	0.1145
3	0.0000	0.0001	0.0114	0.0563	0.1239	0.1714	0.1824	0.1527	0.1145	0.0775
2	0.0001	0.0114	0.0563	0.1239	0.1714	0.1824	0.1527	0.1145	0.0775	0.0486
1	0.0114	0.0563	0.1239	0.1714	0.1824	0.1527	0.1145	0.0775	0.0486	0.0286
-1	0.0563	0.1239	0.1714	0.1824	0.1527	0.1145	0.0775	0.0486	0.0286	0.0161
-2	0.1239	0.1714	0.1824	0.1527	0.1145	0.0775	0.0486	0.0286	0.0161	0.0085
-3	0.1714	0.1824	0.1527	0.1145	0.0775	0.0486	0.0286	0.0161	0.0085	0.0043
-4	0.1824	0.1527	0.1145	0.0775	0.0486	0.0286	0.0161	0.0085	0.0043	0.0021
-5	0.1527	0.1145	0.0775	0.0486	0.0286	0.0161	0.0085	0.0043	0.0021	0.0009
-6	0.1145	0.0775	0.0486	0.0286	0.0161	0.0085	0.0043	0.0021	0.0009	0.0004
-7	0.0775	0.0486	0.0286	0.0161	0.0085	0.0043	0.0021	0.0009	0.0004	0.0003
-8	0.0486	0.0286	0.0161	0.0085	0.0043	0.0021	0.0009	0.0004	0.0003	0.0000
-9	0.0286	0.0161	0.0085	0.0043	0.0021	0.0009	0.0004	0.0003	0.0000	0.0000
-10	0.0161	0.0085	0.0043	0.0021	0.0009	0.0004	0.0003	0.0000	0.0000	0.0000
-11	0.0085	0.0043	0.0021	0.0009	0.0004	0.0003	0.0000	0.0000	0.0000	0.0000
-12	0.0043	0.0021	0.0009	0.0004	0.0003	0.0000	0.0000	0.0000	0.0000	0.0000
-13	0.0021	0.0009	0.0004	0.0003	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
-14	0.0009	0.0004	0.0003	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
-15	0.0004	0.0003	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
-16	0.0003	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0	0.9885	0.9322	0.8083	0.6369	0.4545	0.3018	0.1873	0.1098	0.0612	0.0326



From this point, Harris (1965) considers three different methods of arriving at the long term distribution of final state probabilities for NASN and NASP periods. The one used in this thesis is to "power up" the foregoing yearly transition matrices until each row, or final state, has the same probability value for all ten initial states. In this case, the progressive "squaring" of each set of individual annual matrices to the power of eight, yielded the required series of steady-state probabilities, for winter maximum and summer minimum contents, for each of five standard rates of normal system supply. These probabilities are tabulated in Appendix 12.

#### 5.3.5 Serial Correlation of NASN and NASP Series

The NASN and NASP series, which have been combined to form steady-state probabilities, have so far been assumed to be composed of independent values. This consideration, especially in view of the mutually consecutive nature of these values, requires that an investigation of the degree of serial correlation be made.

TABLE 5.1 : Serial Correlation for NASN and NASP Series  
for a Normal System Supply of 34.6 Ml d<sup>-1</sup>

Paired Variables		Serial Correlation Coefficient
NASN (n)	NASP (n)	-0.12
NASP (n)	NASN (n + 1)	0.090
NASN (n)	NASN (n + 1)	-0.011
NASP (n)	NASP (n + 1)	0.036

As Table 5.1 shows, relevant first and second degree serial correlation coefficients based on 92 pairs of events are of a low order. ~~The directly consecutive pairs of events are of a low order.~~ The directly consecutive paired variables have the more notable levels of serial correlation. Although the two are of a similar order, that between depletion (NASN) and succeeding recharge (NASP) events is negative, whilst the correlation coefficient pertaining to pairs of NASP and directly subsequent NASN events is positive. This would tend to indicate that there is no overall consistent pattern of serial correlation for successive NASN and NASP events.

Harris (1965) discovered similar, but always positive levels of serial correlation, and Lloyd (1963) and Lloyd and Odoom (1964) identified Markovian chain processes in reservoir contents associated with correlation coefficients of 0.1 between paired NASN and NASP events. However, the similar levels of serial correlation displayed in Table 5.1 are of negligible significance. For example, "Statistical Tables" by Fisher and Yates (1963) reveal that for 92 pairs of variables, correlation coefficients of 0.267 and 0.205 are required to prove significance at the 1% and 5% levels of probability respectively, which are the ones normally accepted in statistical practice. The correlation coefficients obtained in this study are even considerably less than that of 0.173, necessary to confirm significance at the 10% level. Therefore, one is led to conclude that the degrees of serial correlation shown in Table 5.1 are not significantly different from zero, and that the NASN and NASP series



are comprised of randomly arranged independent values.

### 5.3.6 Probability of Supply Failure - A First Estimate

The absence of significant levels of serial correlation between NASN and NASP series removes any need for adjustment of the long term distributions of summer minimum and winter maximum steady state probabilities derived in Section 5.3.4, and shown in Appendix 12 for each of five rates of normal system supply.

Such information is that used by previous authors to obtain a probability of failure of a reservoired water supply system. More specifically, the probability of emptiness, or state 0, can be used to derive such a measure. In this case, as Fig. 5.3 shows, state 0 refers to less than 5% of maximum contents at the end of a NASN, or depletion season, and less than 10% at the end of a NASP, or recharge season. If "dead storage", estimated at about 5% of total capacity (Lothian Region Water Supply Services, 1980), is taken into account, then this state gives a valid approximation to the condition of emptiness, at least at the occurrence of summer minimum contents.

Table 5.2 depicts the predicted probabilities of state 0, or emptiness, for both summer minimum and winter maximum contents, for a range of five rates of normal system supply.

At a normal system supply corresponding to the original "reliable yield" of  $42.3 \text{ Ml d}^{-1}$ , the reservoir could be



expected to fail almost one year in two on average. Whereas, at the revised level of  $34.6 \text{ Ml d}^{-1}$ , emptiness is likely to occur in one year in twelve over the long term. Indeed, at the former rate of draw-off, there is even a significant incidence of near-emptiness (ie. less than 10% of maximum storage), with a probability of 0.031 (return period around 30 years), at the occurrence of winter maximum contents.

TABLE 5.2 : Probabilities of Reservoir Storage State 0 (ie. Total Supply Failure) at Summer Minimum and Winter Maximum Contents For Five Levels of Normal System Supply

Normal System Supply ( $\text{Ml d}^{-1}$ )	Probability of State 0					
	Predicted			"Observed"		
	Summer min.	Winter max.	Total	Summer min.	Winter max.	Total
27.3	.012	0	.012	0	0	0
31.8	.036	0	.036	.043	0	.043
34.6	.083	.002	.085	.098	0	.098
37.7	.192	.007	.199	.196	0	.196
42.3	.445	.031	.476	.424	.022	.446

To achieve <sup>ie</sup> the Scottish Development Department's (1973b) desired recurrence interval of instances of supply failure of 50 to 100 years, it would appear that a normal system supply rate of around 25 to  $30 \text{ Ml d}^{-1}$  would be appropriate.

The accuracy and usefulness of the predicted probabilities of emptiness obtained can be assessed by comparison

with frequencies of occurrence of this condition based on the actual 92-year reservoir record. The "observed" probabilities in Table 5.2 refer to the incidence of emptiness which would have occurred over the 92 years, had draw-off from the reservoir corresponded to the standardised rates shown, and had "dead storage" always been 5% of total capacity.

The closeness of the "observed" and predicted probabilities is apparent, especially at the higher rates of normal system supply, where the number of "observed" instances of emptiness is greater. This would indicate that so far, the model for predicting probabilities of reservoir supply failure is satisfactory and reasonably reliable.

#### 5.4 A NEW APPROACH TO DROUGHT MANAGEMENT POLICY FORMULATION

##### 5.4.1 The Incorporation of Deficiency States

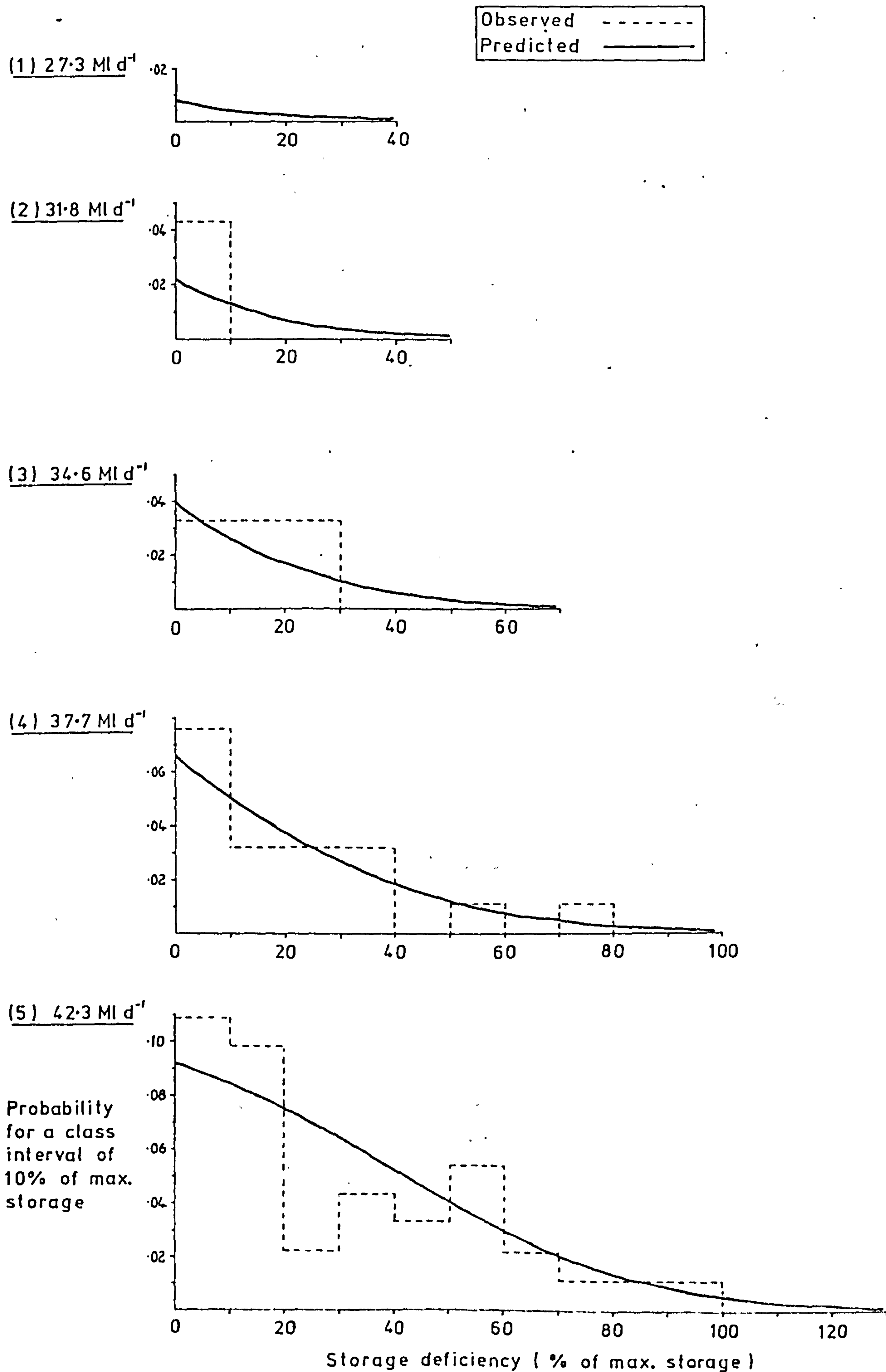
A more detailed assessment of failure probabilities, which includes a measure of the extent of the deficiency of water involved, can be obtained by use of extended NASN matrices, such as that shown in Fig. 5.4 (3). It should be noted here that all following analyses pertain only to such deficiencies incurred at the summer minimum.

It is considered that any realistically operable impounding reservoir supply system in Scotland should have an immeasurably low incidence of failure coinciding with the winter maximum storage level.

The technique presented here makes use of the winter maximum "steady-state" probabilities, tabulated in Appendix 12, which correspond to both final NASP and initial NASN contents. The probabilities corresponding to the ten initial NASN states of 0 to 9 are multiplied with the individual probabilities associated with the various classes of deficiency from final NASN state - 1 down to - 16 (whose values for a normal system supply of  $34.6 \text{ Ml d}^{-1}$  are shown in Fig. 5.4 (3) ). The derived probabilities for each state of deficiency are then summed for the ten values corresponding to each initial NASN state. If, as before the dead storage estimate of 5% is included, then from Fig. 5.3 it can be seen that; state - 1 represents a deficiency of 0 - 10% of maximum storage; state - 2, 10 - 20%, and so on. This allows the association of discrete probabilities with given deficiency states. Curves drawn through the discrete probability values for the mid-point of individual deficiency states are shown in Fig. 5.5, for each of the five adopted levels of normal system supply. Deficiency is measured by percentages of maximum reservoir storage, and the probability scales correspond to a class interval of 10% of maximum storage. These curves provide a means for the estimation of the probability of any deficiency in storage at summer minimum contents for given



**FIGURE 5.5 : Observed and Predicted Probability Curves for Storage Deficiencies at Summer Minimum Contents, for Normal System Supply Rates of:**



levels of normal system supply. It should be noted here that since such deficiencies are measured by volumes of water, then a given shortfall may be more serious at a lower consumption rate, since it will represent a larger number of days supply than for a higher rate of consumption.

The validity and applicability of the probability distributions of deficiency at the summer minimum contents can be gauged by visual comparison with the superimposed histograms on Fig. 5.5. As before, these represent the "observed" frequency of incidences of deficient storage falling within each state, which would have occurred had the supply from Gladhouse Reservoir been operating at the relevant standard levels of normal system supply over the 92 years of record.

Considering that the numbers of "observed" deficiencies are somewhat limited, especially at lower system supply rates, ie. they range from 0 at  $27.3 \text{ Ml d}^{-1}$  to 39 at  $42.3 \text{ Ml d}^{-1}$ , the "observed" and predicted distributions are very similar. Thus, it would seem safe to assume that this technique for estimating the probabilities of various levels of deficiency in summer minimum storage for this reservoir, provides an accurate representation of the frequency of potential events over the 92 years of record.

#### 5.4.2 Intra - Seasonal Probabilities of Storage Deficiency

The method of assessing the probability of summer minimum storage deficiency presented up to this point has

one major limitation. That is, that the probabilities refer to only two discrete and instantaneous moments of the year, ie. those corresponding to winter maximum and summer minimum contents. So far, the only information available on which to base drought management decisions is a series of probabilities determining the likelihood of the former parameter above being followed by given deficiencies in the latter.

Ideally, for a continuous reservoir management programme, what is required is a technique for predicting the probabilities of emptiness, or preferably of the potential extent of storage deficiencies, throughout the NASN season, when reservoir contents are usually progressively decreasing.

Indeed, Lloyd (1970) recognised this lack of measurement of the progression of events, and included a time-dependent or "transient" term in a similar exercise. This feature allowed the analysis of both a quantitative and time-based distribution of reservoir contents. However, as it could only be successfully applied to a 3 - state model reservoir (ie. empty, half full and full), its usefulness is severely limited. A methodology which achieves the above objective is now presented.

The method which has been formulated is now described in some detail with reference to examples. The first step is the construction of a table of cumulative transition probabilities for the extended NASN matrix shown in Fig. 5.4 (3). This involves a simple cumulative summation of the probability values, starting at the base of each



column. The resulting matrix, based on the example above, corresponding to a normal system supply of  $34.6 \text{ Ml d}^{-1}$ , is shown in Fig. 5.6. This matrix yields the probability of the summer minimum (or final NASN) contents being in a given state or lower, for each initial state at the onset of a NASN season. For example, from Fig. 5.6, it can be seen that from an initial state of 8, the probability of the final contents being in state -1 or less (ie. any deficiency) is 0.0612. From a similar starting point, the probability of a final state of 4 or less is 0.4545.

Now, for this example, from an initial state of 8, at the precise moment reservoir contents drop to the progressive state of 4, the new, or intermediate probability of the summer minimum contents being in this state or lower is, of course, unity. This intermediate probability of one corresponds to the top level of final state, 4, ie. 45% of maximum storage.

This allows a new intermediate probability of deficiency to be made, which corresponds to the initial storage state 8 (mid-point 85% of maximum storage), and to the progressive storage level of 45% of maximum. For a deficiency in state -1 or less, the original cumulative probability ( $p_1$ ) of 0.0612, when expressed as a proportion of the cumulative probability which now corresponds to unity ( $p_2$ ), gives the new intermediate probability of the summer minimum contents being in state -1 or lower, ie.

$$\text{intermediate probability} = \frac{p_1}{p_2} \times \text{unity} \quad \dots\dots\dots 6$$

$$(\text{for the above example}) = \frac{0.0612}{0.4545} \times 1.0 = 0.1347$$

FIGURE 5.6 : Cumulative Transition Probabilities for the  
Extended NASN Matrix Corresponding to a  
Normal System Supply of 34.6 Ml d-1  
 (shown in Fig. 5.4 (3) )

Final state	Initial state									
	0	1	2	3	4	5	6	7	8	9
9	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
8	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.9999	0.9885	0.9322
7	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.9999	0.9885	0.9322	0.8083
6	1.0000	1.0000	1.0000	1.0000	1.0000	0.9999	0.9885	0.9322	0.8083	0.6369
5	1.0000	1.0000	1.0000	1.0000	0.9999	0.9885	0.9322	0.8083	0.6369	0.4545
4	1.0000	1.0000	1.0000	0.9999	0.9885	0.9322	0.8083	0.6369	0.4545	0.3018
3	1.0000	1.0000	0.9999	0.9885	0.9322	0.8083	0.6369	0.4545	0.3018	0.1873
2	1.0000	0.9999	0.9885	0.9322	0.8083	0.6369	0.4545	0.3018	0.1873	0.1098
1	0.9999	0.9885	0.9322	0.8083	0.6369	0.4545	0.3018	0.1873	0.1098	0.0612
-1	0.9885	0.9322	0.8083	0.6369	0.4545	0.3018	0.1873	0.1098	0.0612	0.0326
-2	0.9322	0.8083	0.6369	0.4545	0.3018	0.1873	0.1098	0.0612	0.0326	0.0165
-3	0.8083	0.6369	0.4545	0.3018	0.1873	0.1098	0.0612	0.0326	0.0165	0.0080
-4	0.6369	0.4545	0.3018	0.1873	0.1098	0.0612	0.0326	0.0165	0.0080	0.0037
-5	0.4545	0.3018	0.1873	0.1098	0.0612	0.0326	0.0165	0.0080	0.0037	0.0016
-6	0.3018	0.1873	0.1098	0.0612	0.0326	0.0165	0.0080	0.0037	0.0016	0.0007
-7	0.1873	0.1098	0.0612	0.0326	0.0165	0.0080	0.0037	0.0016	0.0007	0.0003
-8	0.1098	0.0612	0.0326	0.0165	0.0080	0.0037	0.0016	0.0007	0.0003	0.0000
-9	0.0612	0.0326	0.0165	0.0080	0.0037	0.0016	0.0007	0.0003	0.0000	0.0000
-10	0.0326	0.0165	0.0080	0.0037	0.0016	0.0007	0.0003	0.0000	0.0000	0.0000
-11	0.0165	0.0080	0.0037	0.0016	0.0007	0.0003	0.0000	0.0000	0.0000	0.0000
-12	0.0080	0.0037	0.0016	0.0007	0.0003	0.0000	0.0000	0.0000	0.0000	0.0000
-13	0.0037	0.0016	0.0007	0.0003	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
-14	0.0016	0.0007	0.0003	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
-15	0.0007	0.0003	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
-16	0.0003	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000



Thus, in this example, for the initial contents of 85% of maximum, when the reservoir level drops to 45% during a NASN season, the probability of any deficiency in summer minimum contents is 0.1347.

This procedure can be applied to all 16 cumulative deficiency probabilities corresponding to states -1 to -16, for each progressive storage state (1 to 9) cumulative probability, and for each initial state. This provides a total of 45 individual progressive cumulative deficiency probabilities for each deficiency state, for each reference system supply rate. A sample of this data for deficiency states -1 to -5 for a normal system supply level of  $34.6 \text{ Ml d}^{-1}$  is shown on Fig. 5.7.

Use of tables such as this allows the probability of a summer minimum storage deficiency in a given state or lower, to be read off when contents enter a given progressive state, in their decline from a particular initial state. For instance, in the example used so far, with an initial state of 8 and a progressive state of 4, it is shown in Fig. 5.7 that the probability of the summer minimum contents being in state -1 or lower is 0.1347. This specific probability therefore applies to any deficiency greater than zero. The band of probability outwith this value, ie. 1 minus 0.1347, can be linked with a maximum possible deficiency of zero. In this way, the limiting probability value of 0.1347 can be associated with a maximum possible deficiency of zero.

Series of such probability values corresponding to limiting deficiency states and deficiency volumes can be



**FIGURE 5.7 : Probabilities of Summer Minimum Contents  
Being in a Given Deficiency State or Lower  
for Given Progressive and Initial NASN  
States, for a Given NSS**

NSS = 34.6 MI d<sup>-1</sup>

Deficiency state	Progressive state	Initial state								
		1	2	3	4	5	6	7	8	9
-1	9									0.0326
	8								0.0619	0.0350
	7							0.1111	0.0657	0.0403
	6					0.1895	0.1178	0.0757	0.0512	
	5				0.3053	0.2009	0.1358	0.0961	0.0717	
	4			0.4598	0.3238	0.2317	0.1724	0.1347	0.1080	
	3		0.6443	0.4876	0.3734	0.2941	0.2416	0.2028	0.1741	
	2		0.8177	0.6832	0.5623	0.4739	0.4121	0.3638	0.3267	0.2969
	1	0.9430	0.8671	0.7880	0.7136	0.6640	0.6206	0.5862	0.5574	0.5327
-2	9									0.0165
	8								0.0330	0.0177
	7							0.0619	0.0350	0.0204
	6					0.1111	0.0657	0.0403	0.0259	
	5				0.1895	0.1178	0.0757	0.0512	0.0363	
	4			0.3053	0.2009	0.1358	0.0961	0.0717	0.0547	
	3		0.4598	0.3238	0.2317	0.1724	0.1347	0.1080	0.0881	
	2		0.6443	0.4876	0.3734	0.2941	0.2416	0.2028	0.1741	0.1503
	1	0.8177	0.6832	0.5623	0.4739	0.4121	0.3638	0.3267	0.2969	0.2696
-3	9									0.0080
	8								0.0167	0.0086
	7							0.0330	0.0177	0.0099
	6					0.0619	0.0350	0.0204	0.0126	
	5				0.1111	0.0657	0.0403	0.0259	0.0176	
	4			0.1895	0.1178	0.0757	0.0512	0.0363	0.0265	
	3		0.3053	0.2009	0.1358	0.0961	0.0717	0.0547	0.0427	
	2		0.4598	0.3238	0.2317	0.1724	0.1347	0.1080	0.0881	0.0729
	1	0.6443	0.4876	0.3734	0.2941	0.2416	0.2028	0.1741	0.1503	0.1307
-4	9									0.0037
	8								0.0081	0.0040
	7							0.0167	0.0086	0.0046
	6					0.0330	0.0177	0.0099	0.0058	
	5				0.0619	0.0350	0.0204	0.0126	0.0081	
	4			0.1111	0.0657	0.0403	0.0259	0.0176	0.0123	
	3		0.1895	0.1178	0.0757	0.0512	0.0363	0.0265	0.0198	
	2		0.3053	0.2009	0.1358	0.0961	0.0717	0.0547	0.0427	0.0337
	1	0.4598	0.3238	0.2317	0.1724	0.1347	0.1080	0.0881	0.0729	0.0605
-5	9									0.0016
	8								0.0037	0.0017
	7							0.0081	0.0040	0.0020
	6					0.0167	0.0086	0.0046	0.0025	
	5				0.0330	0.0177	0.0099	0.0058	0.0035	
	4			0.0619	0.0350	0.0204	0.0126	0.0081	0.0053	
	3		0.1111	0.0657	0.0403	0.0259	0.0176	0.0123	0.0085	
	2		0.1895	0.1178	0.0757	0.0512	0.0363	0.0265	0.0198	0.0146
	1	0.3053	0.2009	0.1358	0.0961	0.0717	0.0547	0.0427	0.0337	0.0261

used to derive two very useful series of relationships. The first are those between limiting deficiency probability (LDP) values, and the corresponding maximum possible deficiency, defined by the area of probability outwith this value. Sets of curves for each progressive state during the NASN season can be formed in this way. An example on Fig. 5.8, pertaining to a normal system supply of  $34.6 \text{ Ml d}^{-1}$  and an initial state of 8, shows the series of curves describing the above relationship for progressive states 8 to 1, for minimum possible summer minimum deficiency states from -1 to -4.

The vertical scale on the right of Fig. 5.8 depicts the largest possible deficiency, in terms of percent of maximum reservoir storage, for each minimum possible summer minimum deficiency state. These are the values used from here on, since although they may involve some over-estimates of storage deficiency at final contents, they do account for all possible deficiencies in a deficiency state range. In addition, instead of using "progressive states" to describe declining reservoir contents during NASN seasons, it is more appropriate to refer to the percent of maximum storage at the onset of such states, which are indicated on the column on the right of Fig. 5.3.

A subsequent, and more useful series of curves, which can be derived from the type of data shown in Fig. 5.7, relates the top value of progressive state storages to predicted maximum possible final state deficiencies, for given levels of LDP. An example, based on the same sample

FIGURE 5.8 : A Series of Curves Relating Limiting Deficiency Probability and Maximum Possible Summer Minimum Storage Deficiency for Each Progressive NASN State, for the Undernoted Standard Conditions

NSS = 34.6 MI d<sup>-1</sup>

Initial state = 8

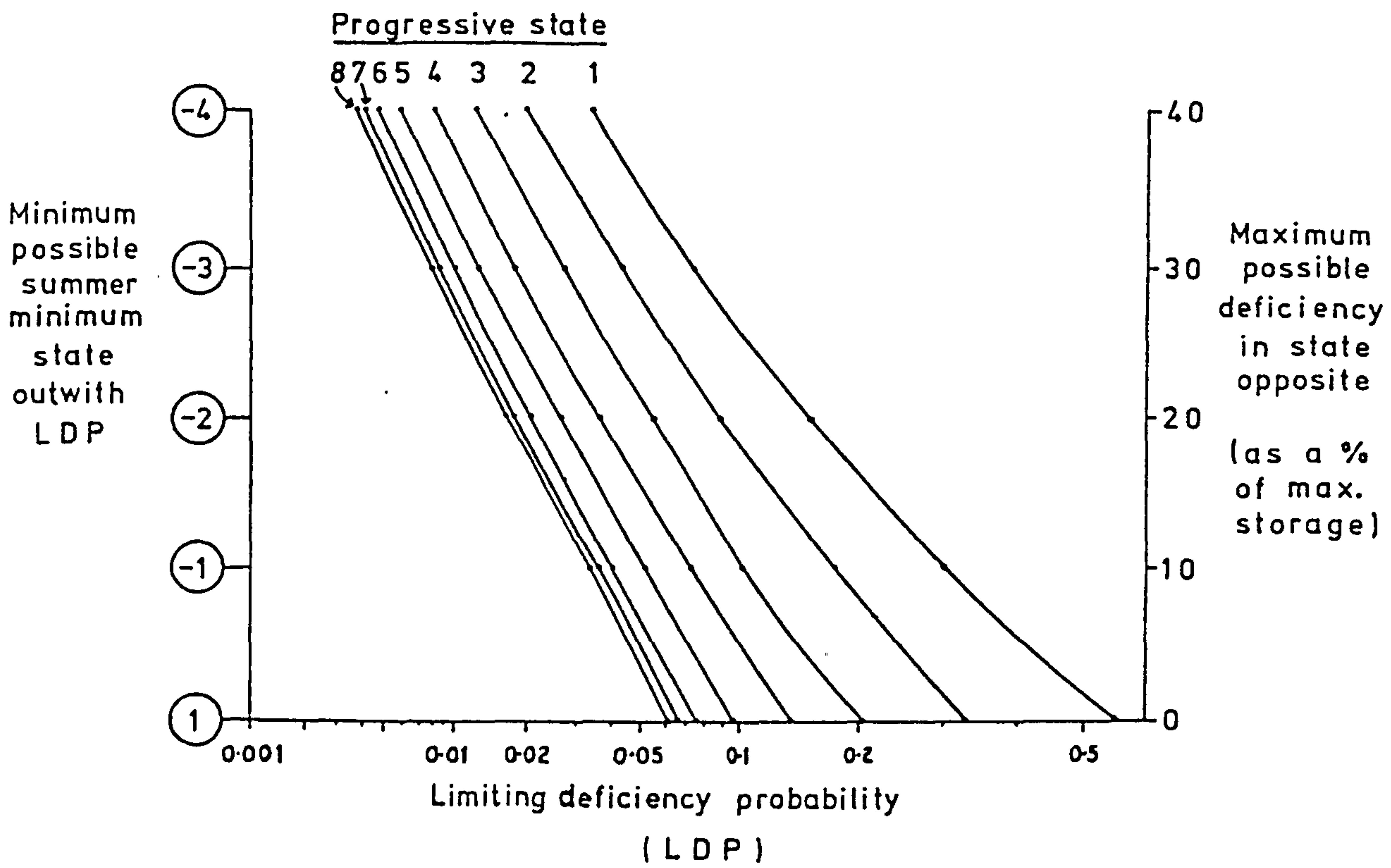
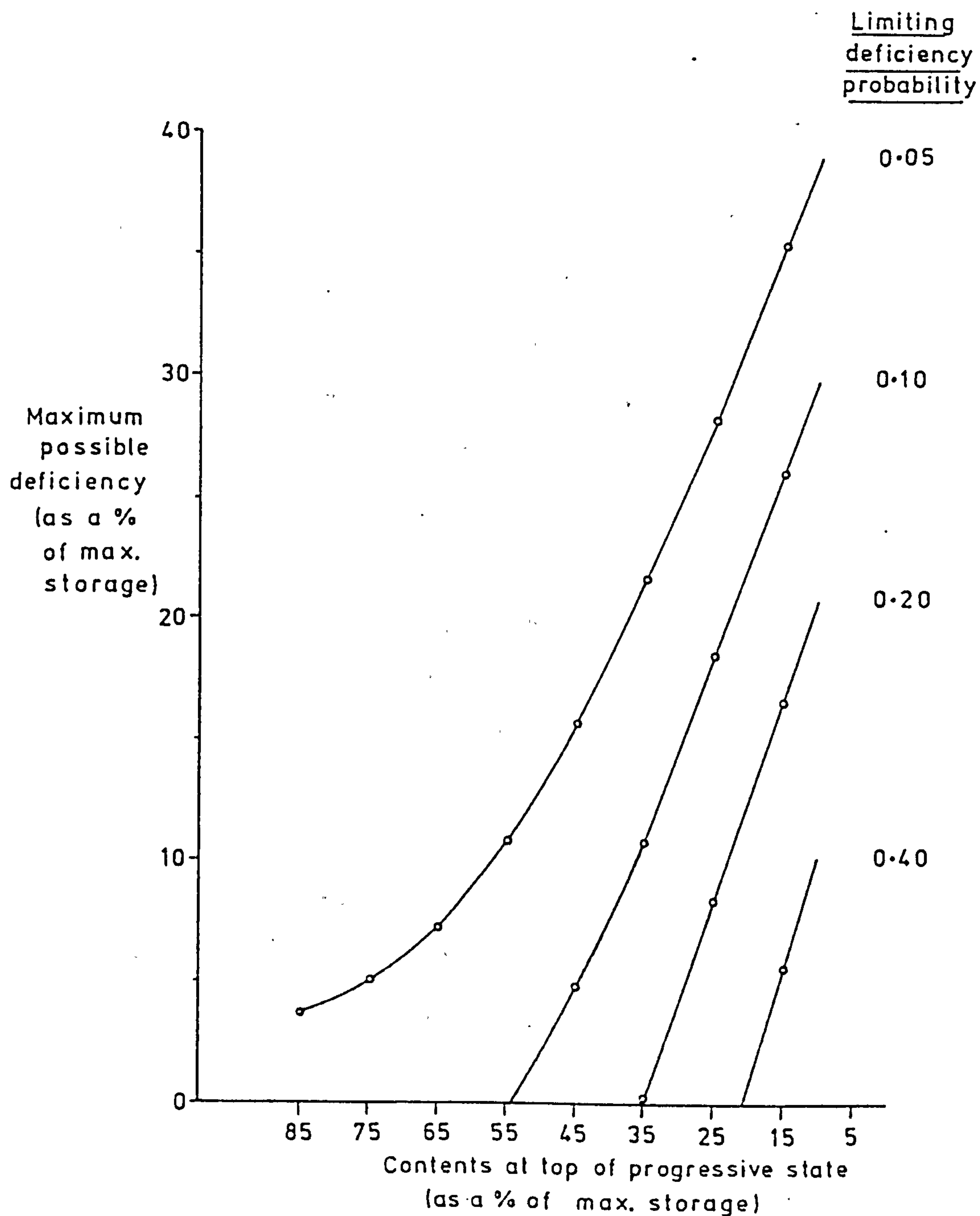




FIGURE 5.9 : A Series of Curves Relating Progressive NASN Contents and Maximum Possible Summer Minimum Storage Deficiency for Given Levels of Limiting Deficiency Probability, for the Undernoted Standard Conditions

NSS = 34.6 MI d<sup>-1</sup>

Initial contents = 85 %



data as above, is shown in Fig. 5.9, for limiting deficiency probabilities of 0.05, 0.10, 0.20 and 0.40. Such curves can be used to predict the maximum possible deficiency at any given level of declining storage, for given conditions of; limiting deficiency probability (LDP); initial NASN contents (ie. winter maximum storage state); and level of normal system supply (NSS).

A complete series of such curves relating to; LDP values ranging from 0.05 to 0.50; initial contents from states 1 to 9; and the five normal system supply rates listed earlier, has been derived. This was done on the computer mentioned earlier, using data such as that shown in Fig. 5.7, and a minimax polynomial curve fitting procedure provided by the Nottinghamshire Algorithm Unit (1977). Five-degree polynomials were discovered to be sufficient to describe all resultant curves, and were used throughout. Iteration of the relevant polynomial equations was used to find the level of declining reservoir contents at which, for a given LDP, the occurrence of a maximum possible deficit of zero would occur. This value determines the critical storage level at which curves such as those in Fig. 5.9 meet the x-axis.

#### 5.4.3 Derivation of Drought Management Measures to

##### Make Temporary Reductions to the Normal System Supply

The developments so far, in that they enable progressive probability estimates of deficiencies in storage

at summer minimum contents to be made, provide a useful basis for reservoir management decisions to be made in times of actual or threatened drought.

This section considers a method of using this type of information in relation to the reductions to NSS required to prevent potential deficiencies at the end of NASN seasons. The necessary long term annual probabilities of given levels of reduction to NSS can then be assessed. An initial complication is included by the need to choose a given probability level of storage deficiency at the end of a NASN season as a basis for the calculation of necessary reductions to NSS. Obviously, it would be impossible to take account of all possible deficiencies, therefore a "cut-off" point for the probability level of deficiencies is required. This function is fulfilled by the limiting deficiency probability (LDP) values, as defined and calculated in the previous section. An LDP value marks the extreme portion of intermediate probability during a NASN season, which is ignored in the assessment of potential storage deficiencies to be catered for.

A further complication is presented by the fact that the analysis, as it stands, includes no measure of time. This is essential, since, when considering a given potential storage deficiency which has to be prevented by a reduction to the normal system supply during a NASN season, information is required as to the time available over which the necessary savings can be effected. The relationship



between volumes of water and durations involved in NASN events can be used as a basis for the estimation of relevant time periods.

Fig. 5.10 illustrates the scatter of the 92 pairs of the above variables for all NASN events from 1885 to 1976 at Gladhouse Reservoir, adjusted to a normal system supply (NSS) of  $34.6 \text{ ML d}^{-1}$ . It is notable that the range of variation in NASN season duration decreases greatly as NASN volumes increase. However, the lack of an overall definitive relationship is indicated by a correlation coefficient of only 0.67. The minimum limit is well defined by a line corresponding to an average net inflow rate (ie. actual inflow minus surface evaporation) of  $4.5 \text{ ML d}^{-1}$ . The average rate of net inflow (in  $\text{ML d}^{-1}$ ) over a given period of days from  $d_1$  to  $d_2$  is given by;

$$\text{NSS} = \frac{\text{NASN}_2 - \text{NASN}_1}{d_2 - d_1} \dots\dots\dots 7$$

where ; NSS = normal system supply ( $\text{ML d}^{-1}$ );  
 $\text{NASN}_1$  = the drop in storage accumulated at  $d_1$  (ML);  
 $\text{NASN}_2$  = the drop in storage accumulated at  $d_2$  (ML).

Use of such information by a reservoir manager in time of drought is best illustrated by an example. From Fig. 5.9, it can be seen that for an initial content of 85% full, when the storage declines to 25% of maximum, at the 0.20 level of LDP, the maximum potential deficiency is 8% of maximum storage, ie. 650 ML. If, for the moment, it is

assumed that this level of LDP is the appropriate value for the management of this particular reservoir, then the required reduction in NSS is derived by the following means. The relevant changes in storage can be summarised as follows:

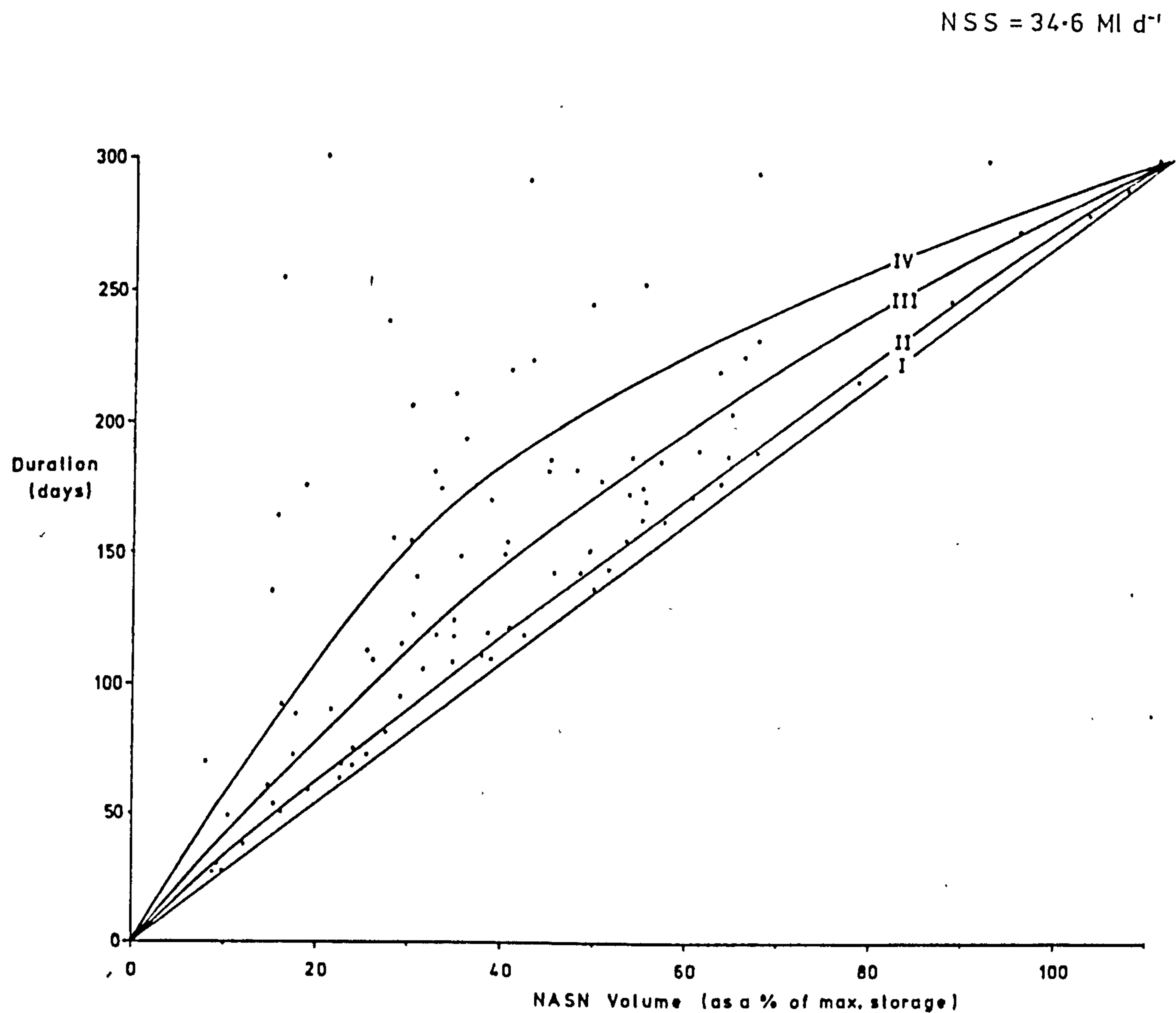
$$\text{intermediate NASN to date} = 85\% - 25\% = 60\%$$

$$\begin{aligned} \text{Total potential NASN} &= \text{initial contents} - \text{dead storage} + \text{potential deficiency} \dots 8 \\ &= 85\% - 5\% + 8\% = 88\% \end{aligned}$$

The number of days during the NASN season to date will be known, and should lie somewhere above 162, as Fig. 5.10 indicates for a NASN of 60% of maximum capacity. Similarly, the total length of the potential NASN of 88% of maximum capacity can be expected to be at least 238 days. As intimated earlier, this fall in 28% of capacity (2277Ml) over a period of 238 minus 162 days (76 days), at an NSS of  $34.6 \text{ Ml d}^{-1}$ , corresponds to the average minimum net inflow rate of  $4.5 \text{ Ml d}^{-1}$ .

If, when contents are at 25% as above, the reservoir manager considers this to be a likely level of net inflow in the short term future, then a period of 76 days can be allowed for the potential deficiency to occur. However, with a knowledge of existing inflow rates, the recession behaviour of streams supplying the reservoir, and likely evaporation rates, a correspondingly longer period can be allowed for the potential drop in storage under consideration. If there is any doubt, the time period above, of 76 days, corresponding to the average minimum net inflow rate could be used.

**FIGURE 5.10 : The NASN/Duration Relationship, and Its Division Into Four Discrete and Equally Probable Parts, for a Given NSS**





The temporary system supply rate (TSS), required to avoid the relevant potential deficiency in storage associated with this time period, is given by;

$$\text{TSS} = \text{NSS} - \frac{\text{Potential deficiency}}{\text{No. days available}} \dots\dots\dots 9$$

where;

NSS = normal system supply.

Inserting the data for the example above,

$$\begin{aligned} \text{TSS} &= 34.6 - \frac{650}{76} \\ &= 26.0 \text{ Ml d}^{-1} \end{aligned}$$

This temporary draw-off rate represents 75% of the normal system supply of 34.6 Ml d<sup>-1</sup>, and therefore, a 25% reduction in NSS would be required to implement this particular drought management measure.

In order to represent as best as possible the entire range of durations associated with NASN volumes, for inclusion in a predictive model, it was decided to divide the scatter of points shown in Fig. 5.10 into discrete units of known probability, in order to simulate the possible range of actual events. The consequent simplification and generalisation of this type of relationship into four equally probable parts is shown by the series of curves on Fig. 5.10. These curves were fitted subjectively, by eye, but each was drawn to form four classes each containing one quarter of the total 92 values.

The potentially deficiency - causing NASN values, such as those in the above example derived from Fig. 5.9,

can now be used to give four discrete duration values for each NASN volume. In all cases, the NASN durations used are those coinciding with the minima in each portion of the distribution. Therefore, the values on the curves themselves are those used to compute the four equally probable durations for each NASN value. This is done to err on the side of safety, and can involve a slight overestimation in the extent of necessary reductions in NSS. However, the following examples indicate that the range of values concerned is typically very small.

If the assumption is made that the net inflow during each defined total NASN period is constant ( a contention which is validated by the near-constant gradient NASN events such as those illustrated earlier in Fig. 4.3), it is a relatively simple matter to use the foregoing procedure to compute the necessary reductions in NSS required to prevent potential deficiencies in storage at the summer minimum contents.

Using the appropriate duration from curves, such as I to IV on Fig. 5.10, for the total potential NASN event under concern, the number of days available for the remaining part can be assumed to be the proportion of the total duration represented by the volumes of water pertaining to;

$$\frac{\text{remaining potential NASN}}{\text{total potential NASN}}$$

Values obtained using the four curves on Fig. 5.10 for the sample data used so far (and shown below), can be used as an illustrative example. As usual, all volumes of

water are expressed as a percentage of the reservoir's capacity.

initial contents	=	85%		
intermediate contents	=	25%		
LDP	=	0.20		
total potential NASN	=	88%		
potential deficiency	=	8%		
NSS	=	34.6 Ml d <sup>-1</sup>		
NASN/duration curve	I	II	III	IV
No. days available	76	78	82	86
TSS (Ml d <sup>-1</sup> )	26.0	26.3	26.6	27.0

Notably, the reduced system supply rates are almost the same in all four circumstances. This is because the range of durations which correspond to a large NASN event tends to be small, as Fig. 5.10 reveals. In this case, where a total potential NASN of 88% of maximum storage is involved, the four values for the required alterations to NSS correspond to reductions in water usage in the range of 22 to 25 percent. As such narrowly defined ranges are always the case in this simulated model, where large NASN events are concerned, then the aforementioned degree of subjectivity needed for individual drought management decisions is largely removed.

A second example, involving a relatively small NASN event can be used to illustrate the typical level of subjective assessment required in such circumstances. Details relevant to this example are given overleaf.



initial contents	=	55%
LDP	=	0.20
total potential NASN	=	59%
potential deficiency	=	9%
NSS	=	34.6 Ml d <sup>-1</sup>

In this instance, at the winter maximum (initial) contents of 55%, there is an immediate potential storage deficiency of 9%, corresponding to an LDP of 0.20. Using the curves on Fig. 5.10, the following values are obtained.

NASN/duration curve	I	II	III	IV
No. days available	159	169	195	224
TSS (Ml d <sup>-1</sup> )	30.1	30.3	30.9	31.3

The range of reductions required to NSS under these flow circumstances is again of small proportions, ie. 10 to 13%. Therefore, the subjective element allowed for in each drought management decision in such circumstances is very limited. If, in an unpredictable inflow situation, the drought manager opts for the most severe NSS reduction, then the extent of possibly unnecessary hardship imposed on consumers is very slight.

Only where very small potentially deficiency-causing NASN events are involved (say less than 40% of maximum storage), can there be considerable uncertainty involved as to the degree of reduction to NSS required. This could only occur when; NASN volumes are less than 40% (probability at NSS of 34.6 Ml d<sup>-1</sup> = 0.68); winter maximum contents are less than 45% (probability = 0.028); and the

LDP is high, say greater than 0.3. Thus, for high LDP's, at an NSS rate of  $34.6 \text{ Ml d}^{-1}$ , the probability of both the above circumstances is  $0.68 \times 0.028$ , which is around 0.02.

Therefore, the degree of subjective flexibility included in this drought management simulation model, which pertains to the variation in NASN season inflow rates is, for at least 98% of occasions, at a realistically small level, for an NSS rate of  $34.6 \text{ Ml d}^{-1}$ , and LDP of 0.30. At lower NSS rates, when winter maximum contents are less likely to be at low levels, this percentage is higher.

This would indicate that the four-part model to simulate the variation in duration for given NASN events is acceptable, and that drought management measures associated with each can be assumed to be approximately equally probable, and in accordance with what would be actual events.

#### 5.4.4 Continuous Drought Management Programmes

In any impending drought situation, or any other NASN season for that matter, it would be desirable to monitor continuously the probabilities of deficiency in storage, and the possible levels of reduced draw-off required to prevent supply failure.

The techniques outlined previously allow such a series of actions to be simulated on a computer model, which makes continuous use of a given LDP value to assess

necessary reductions to NSS. The sequence of operations involved is shown in diagrammatic form in Fig. 5.11. In this instance, reservoir contents are reviewed at ten day intervals, because this would seem to represent a period long enough to assess relevant changes in storage conditions, and adequately short to allow for successive effective reductions in consumption to be made. This interval could easily be adjusted to, say, seven or fourteen days, to suit the pattern of working days.

The flowchart on Fig. 5.11 was used as the basis for a computer programme which includes an accounting procedure for all the relevant variables, both actual, and potential (as if the NSS remained permanently unaltered). The latter values are required for the relationships between storage (at NSS) and potential deficiency, such as shown in Fig. 5.9. An example of the computer output, based on the sample data used so far, ie.

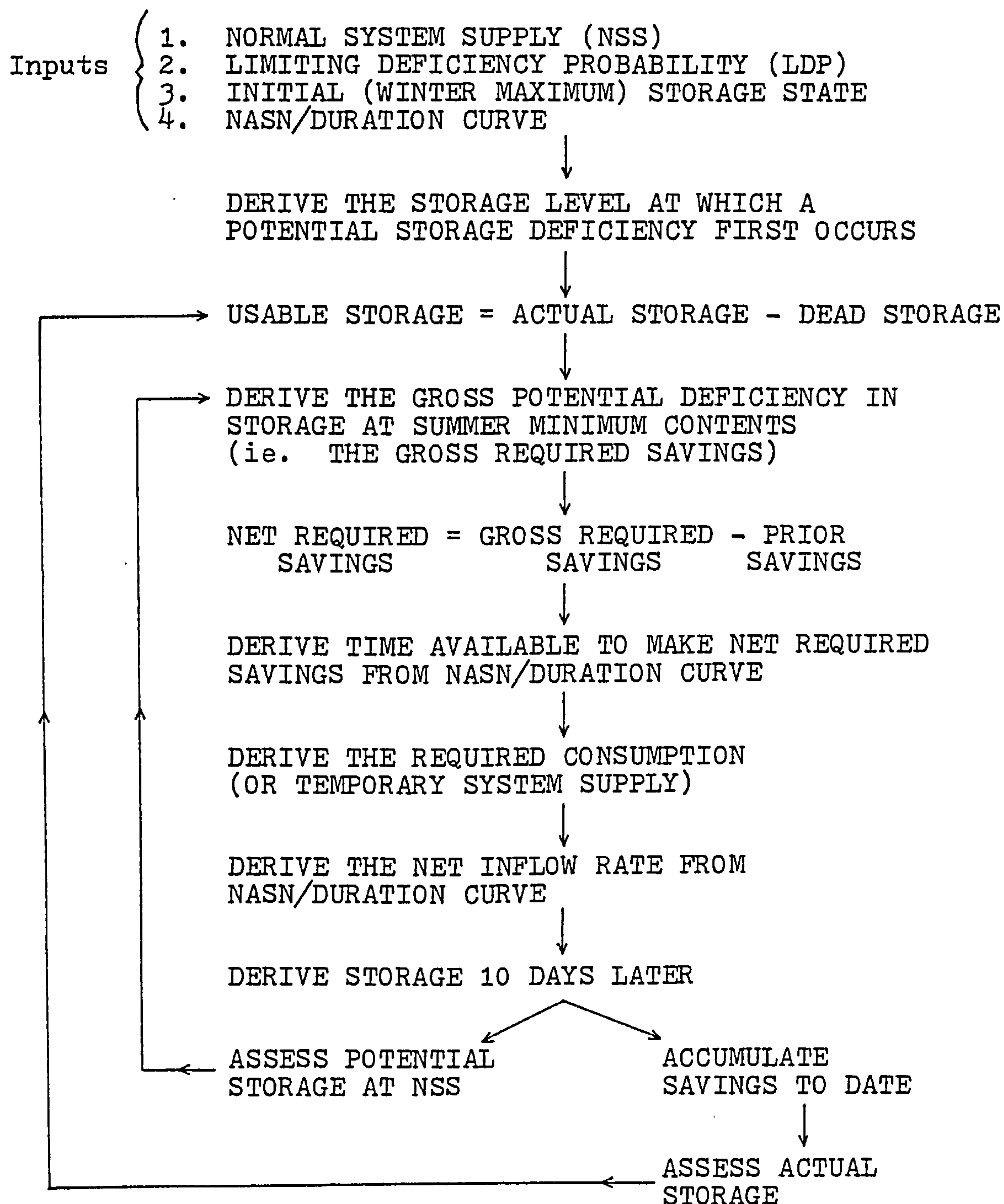
NSS	=	34.6 Ml d <sup>-1</sup>
LDP	=	0.20
initial state	=	8 (contents= 85%)

NASN/duration curve I

is shown in Fig. 5.12. Under these circumstances, as this information reveals, when contents drop to 35.1%, a potential deficiency is only just avoided. However, ten days later, when contents have dropped to 31.4%, the 3% potential deficiency requires that the system supply should be reduced to 32 Ml d<sup>-1</sup>. Progressively lower storage levels involve progressively larger net potential deficiencies and correspondingly



FIGURE 5.11 : Design of the Computer Model Which Simulates  
Continuous Drought Management Programmes



**FIGURE 5.12 : A Sample of the Output From the Computer Model Producing Simulated Sequences of Drought Management Measures, for the Undernoted Inputs**

NSS = 34.6 MI d<sup>-1</sup>

LDP = 0.20

Initial state = 8

NASN/duration curve I

Storage (% of maximum)			Savings (% of max storage)			Required Consumption (or TSS)		Time interval	
Pot- ential	Actual	Usable	Gross required	Cumul- ative to date	Net required	MI d <sup>-1</sup>	% of NSS	days	cumul- ative days
35.1	35.1	30.1	0.0	0.0	0.0	34.6	100.0		
								10.	10.
31.4	31.4	26.4	3.0	0.0	3.0	32.0	92.3	10.	20.
27.7	28.0	23.0	5.8	0.3	5.5	29.7	85.8	10.	30.
24.0	24.9	19.9	8.7	0.9	7.8	27.6	79.7	10.	40.
20.3	22.1	17.1	11.6	1.8	9.8	25.6	74.0	10.	50.
16.6	19.5	14.5	14.5	2.9	11.6	23.8	68.7	10.	60.
12.9	17.1	12.1	17.5	4.2	13.2	22.1	63.7	10.	70.
9.2	15.0	10.0	20.4	5.8	14.6	20.5	59.2	10.	80.
5.5	13.0	8.0	23.3	7.5	15.8	19.1	55.0	10.	90.
1.8	11.2	6.2	26.3	9.4	16.8	17.7	51.2	10.	100.
-1.9	9.6	4.6	29.2	11.5	17.7	16.5	47.7	10.	110.
-5.6	8.1	3.1	32.1	13.7	18.4	15.4	44.4	10.	120.
-9.3	6.8	1.8	35.1	16.1	18.9	14.4	41.4	10.	130.
-13.0	5.6	0.6	38.0	18.6	19.4	13.4	38.7	10.	140.

greater reductions to NSS. For example, at one hundred days into this simulated sequence of drought management measures, the reservoir contents have dropped to 9.6% of the maximum, and the necessary temporary draw-off rate is less than half of the NSS, at  $16.5 \text{ Ml d}^{-1}$ .

The progression of events regarding actual storage, and the system supply rates required to prevent the occurrence of the deficiencies corresponding to the 0.20 LDP level are shown on Fig. 5.13, along with similar curves for limiting deficiency probability levels of 0.10 and 0.40. All these curves refer to NASN/duration curve I on Fig. 5.10, and thus correspond to minimum inflow rates. Similar curves based on curves II to IV follow paths displaced slightly upwards. This displacement is so small however, that on the scale shown in Fig. 5.13, the four curves would be indistinguishable. Such curves, strictly speaking, should, in keeping with the nature of the computer model, be composed of discrete ten day steps. However, the use of smoothed curves, whilst not deviating significantly from the actual "stepped" path, facilitates the comparison of different patterns of events.

As Fig. 5.13 indicates, the lower the limiting deficiency probability utilised, the earlier the reductions to NSS have to be made, ie. when reservoir contents are still relatively high. This has the effect of conserving greater quantities of water for use in the latter stages of a potential severe drought event. Consequently, reductions in NSS are comparatively less severe in progression when



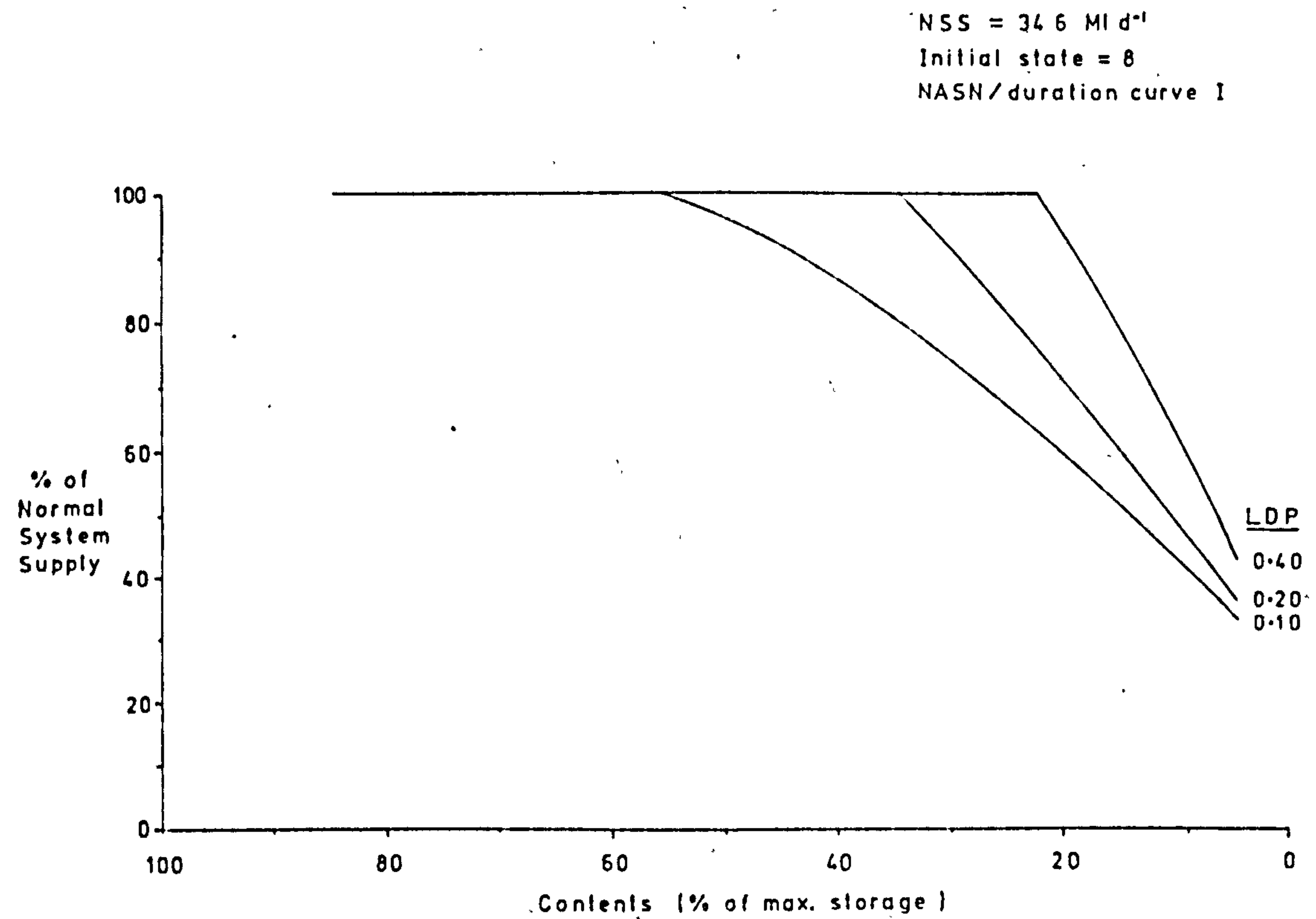
lower LDP's are employed, as is shown by the more gentle gradient of the curve relating to an LDP of 0.10 in Fig. 5.13.

A further feature of these curves which also applies to the general case, is the convergence involving the various LDP values. Generally, this convergence tends towards minimum consumption levels of 30 to 35% of NSS, indicating that the maximum required reduction would be around 65 to 70%.

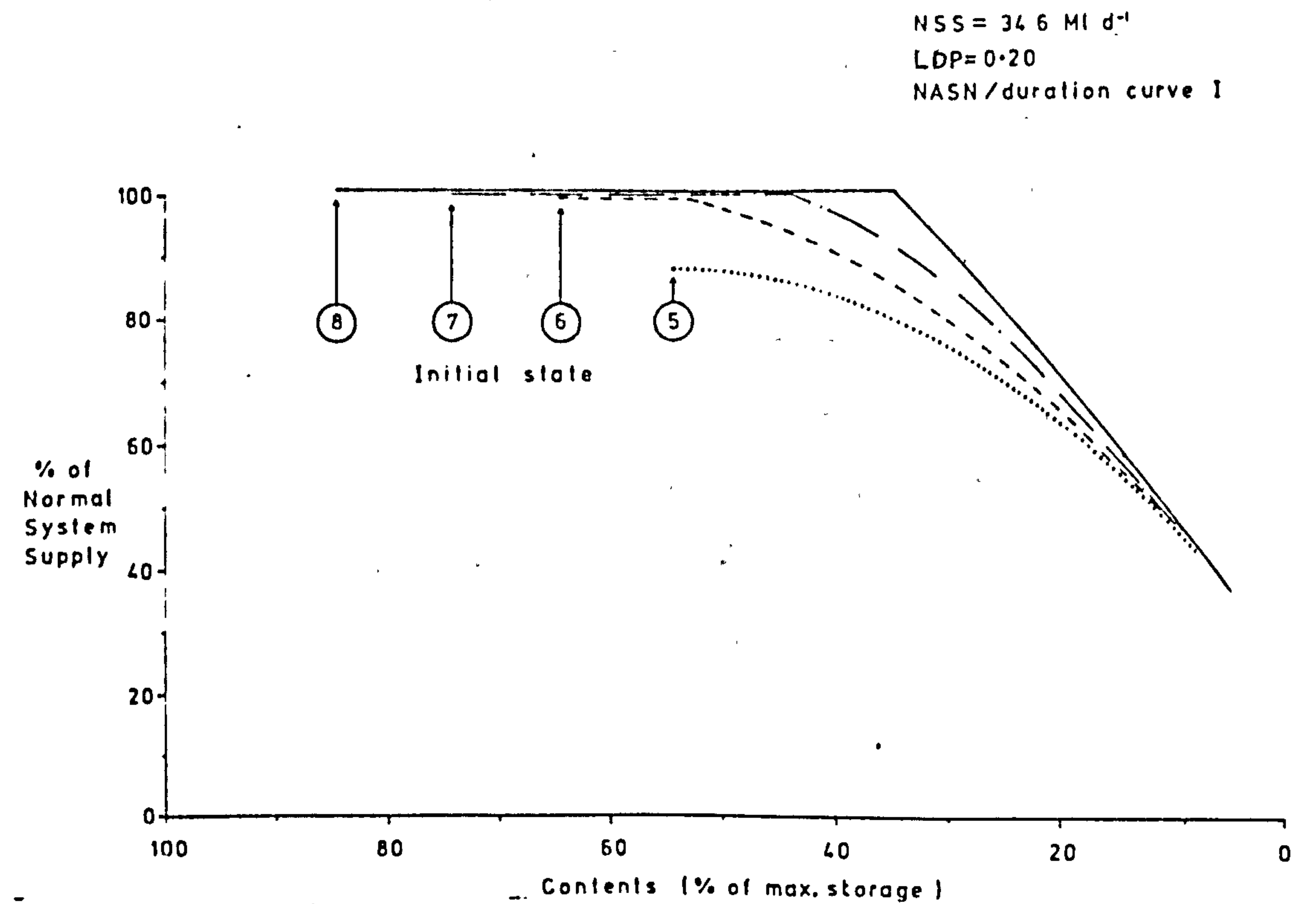
Fig. 5.14 shows the same type of curves as above, however in this case the simulated patterns of events from four different initial storage levels are compared for standard conditions of, an LDP of 0.20 and NASN/duration curve I.

As the initial (winter maximum) contents decrease from 85% full (state 8) to 55% (state 5), so the storage level at which reductions to NSS become necessary is higher. Thus, the time period over which normal system supply can be maintained is shorter. For the lowest initial contents level shown in Fig. 5.14, ie. 55%, this period is in fact zero. As indicated earlier, in this case, using an LDP of 0.20, a reduction to NSS is required at the onset of the NASN season. Fig. 5.14 reveals that an immediate reduction to 87% of NSS is necessary. At this LDP level, initial contents lower than the above value require more severe immediate NSS reductions. This severity will be greater the lower the limiting deficiency probability level employed.

**FIGURE 5.13 : Comparison of Simulated Continuous Drought Management Programmes Using Different Levels of LDP for Given Standard Conditions**



**FIGURE 5.14 : Comparison of Simulated Continuous Drought Management Programmes Starting from Different Initial Storage States for Given Standard Conditions**



The simulated sequence of reductions to NSS shown in Fig. 5.14 indicates that from the onset of a drought management programme, the reductions up to around 50% of NSS are progressively more severe for conditions of initially higher storage. An exception of course occurs when initial contents are so low as to merit immediate reductions in draw-off rate. As an example of the general case, at 50 days into the drought management procedure simulated on Fig. 5.14, the required reductions to NSS are 11 to 17% for initial contents of 65%, and 25 to 31% for initial contents of 85% (depending on which of the four NASN/duration relationships is used).

This feature is decreasingly apparent the further storage continues to decline, and the same pattern of convergence towards maximum reductions to NSS of around 70% is again apparent.

#### 5.4.5 Application of the Simulated Drought Management Procedures to the Real Situation

So far, only rigidly defined and simulated NASN events, which can be taken to be representative of actual possible events, have been considered. In the real situation, however, drought management of a reservoired water supply resource will be subject to further variables. For instance, inflows will not conform to the precisely defined and generalised patterns used so far, and desired reductions to NSS may not be achieved at the required level,



or at the required time. Such imponderables can, however, be included in the process outlined in Fig. 5.11, and therefore taken into account each time potential deficiencies in summer minimum storage, and necessary reductions to NSS are calculated. This system of drought management includes a considerable degree of flexibility, which is required for individual circumstances, and it should be noted that curves such as those on Figs. 5.13 and 5.14 do not represent hard and fast rules<sup>for</sup> reservoir supply system management, but only a simulated sequence of actions geared to deal with a given sample of specific circumstances.

## 5.5 A NEW APPROACH TO RELIABLE YIELD FORMULATION FOR RESERVOIRED WATER SUPPLY SYSTEMS

### 5.5.1 Derivation of Long Term Probabilities of Reductions to NSS

Information such as that shown in Fig. 5.12 has been obtained for;

- (i) all individual winter maximum storage states;
- (ii) each of the four equally probable NASN/duration relationships.

This can be used as the basis for an assessment of the long term probabilities of given reductions in consumption.

The same procedures outlined so far have also been applied to all five adopted NSS values mentioned earlier, thus allowing a similar assessment to be made in each case.

The first step in this technique is to form a relationship between "potential storage" (ie. that which would occur had the rate of consumption remained unaffected) and "percent of NSS", using paired values such as in Fig. 5.12. This was done on computer using five degree polynomials fitted by NAG subroutine E02ACF (Nottinghamshire Algorithm Unit, 1977). For each specific set of conditions, this allows the reductions to NSS to be associated with specific values of potential storage.

Secondly, a similar type of relation can be calculated for "potential storage" and probability. This involves using the relevant initial (winter maximum) state's column of cumulative probabilities, such as those shown in Fig. 5.6. By associating the top value of each final (summer minimum) state with the probability of being in that state or lower, the necessary relation is formed, for each specific condition of NSS and initial (winter maximum) contents.

Subsequently, potential storage values corresponding to given percentage reductions to NSS derived from the relationship in the first step, can be inserted into the second to provide probability estimates of the long term occurrence of such reduced rates of consumption.

Then, if these probabilities are multiplied by 0.25 for each of the four equally probable NASN/duration



classes, and the four values summed, the relative probabilities of given reductions to NSS are obtained for each initial contents state. If for each of these states, these probabilities are multiplied by the probabilities of starting from this given level of reservoir contents (shown in Appendix 12), the absolute probabilities of given reductions in consumption can be derived.

Such information displaying the relative and absolute probabilities of successive additional 10% reductions to NSS, for each initial state, is shown in Fig. 5.15, parts (1) and (2) respectively. This example refers to an NSS of  $34.6 \text{ Ml d}^{-1}$  and a limiting deficiency probability of 0.20. The last column in Fig. 5.15 (2) represents the sum of all initial state probabilities for each level of consumption reduction, and thus indicates the total long term recurrence probabilities of given levels of reduction to an NSS of  $34.6 \text{ Ml d}^{-1}$ , if Gladhouse Reservoir was managed along the lines defined by an LDP of 0.20.

It should be noted that the probabilities for 0% reductions in fact refer to situations where a reduction is only just unnecessary. The probability of there being no reductions at all in any NASN season is given by 1.0 minus this probability.

With reference to the relative probabilities, these can be seen to decrease with, (i) increasing levels of consumption reduction; and (ii) increasing initial storage states.

The pattern for the absolute probabilities is more complicated. For example, whilst the relative probability



FIGURE 5.15 : The Expected Incidence of Given Percentage Reductions to NSS for the Undernoted Conditions in Terms of:

NSS = 34.6 MI d<sup>-1</sup>  
LDP = 0.20

(1) Relative probability

% redn. to NSS	Initial state									
	0	1	2	3	4	5	6	7	8	9
0	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.9274	0.6836	0.3028	0.1498
10	1.0000	1.0000	1.0000	1.0000	1.0000	0.9730	0.6831	0.4059	0.2349	0.1247
20	1.0000	1.0000	1.0000	0.9885	0.9702	0.6610	0.4595	0.2873	0.1717	0.0969
30	1.0000	1.0000	0.9874	0.9547	0.6665	0.4460	0.3082	0.1981	0.1203	0.0688
40	1.0000	1.0000	0.9316	0.4648	0.4197	0.2813	0.2007	0.1282	0.0800	0.0448
50	1.0000	1.0000	0.3381	0.2451	0.2216	0.1527	0.1179	0.0792	0.0479	0.0261
60	1.0000	0.9813	0.1811	0.1279	0.1188	0.0827	0.0612	0.0405	0.0223	0.0117
70	0.9444	0.2855	0.1105	0.0912	0.0720	0.0516	0.0327	0.0075	0.0049	0.0018
80	0.8888	0.2432	0.0674	0.0455	0.0244	0.0142	0.0106	0.0035	0.0024	0.0004
90	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
100	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

(2) Absolute probability

% redn. to NSS	Initial state										Total for all states
	0	1	2	3	4	5	6	7	8	9	
0	0.0018	0.0037	0.0077	0.0133	0.0212	0.0317	0.0415	0.0403	0.0222	0.1114	0.2946
10	0.0018	0.0037	0.0077	0.0133	0.0212	0.0311	0.0305	0.0239	0.0172	0.0927	0.2432
20	0.0018	0.0037	0.0077	0.0133	0.0208	0.0212	0.0205	0.0169	0.0126	0.0721	0.1905
30	0.0018	0.0037	0.0077	0.0129	0.0143	0.0143	0.0138	0.0117	0.0088	0.0516	0.1405
40	0.0018	0.0037	0.0073	0.0063	0.0090	0.0090	0.0090	0.0075	0.0059	0.0343	0.0937
50	0.0018	0.0037	0.0026	0.0033	0.0048	0.0050	0.0054	0.0048	0.0036	0.0204	0.0555
60	0.0018	0.0036	0.0014	0.0017	0.0025	0.0026	0.0027	0.0024	0.0016	0.0087	0.0291
70	0.0017	0.0011	0.0009	0.0012	0.0015	0.0016	0.0015	0.0004	0.0004	0.0014	0.0117
80	0.0016	0.0009	0.0005	0.0006	0.0005	0.0005	0.0005	0.0002	0.0002	0.0003	0.0058
90	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
100	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

of necessary reductions to NSS are smallest for the highest initial state of 9, the corresponding absolute levels are generally highest because this is by far the most common initial (winter maximum) state.

As mentioned earlier, at all initial contents less than the level of state 6, there is always a requirement for immediate consumption reductions. This necessity, indicated by a relative probability of 1.0, is progressively more severe for lower initial states.

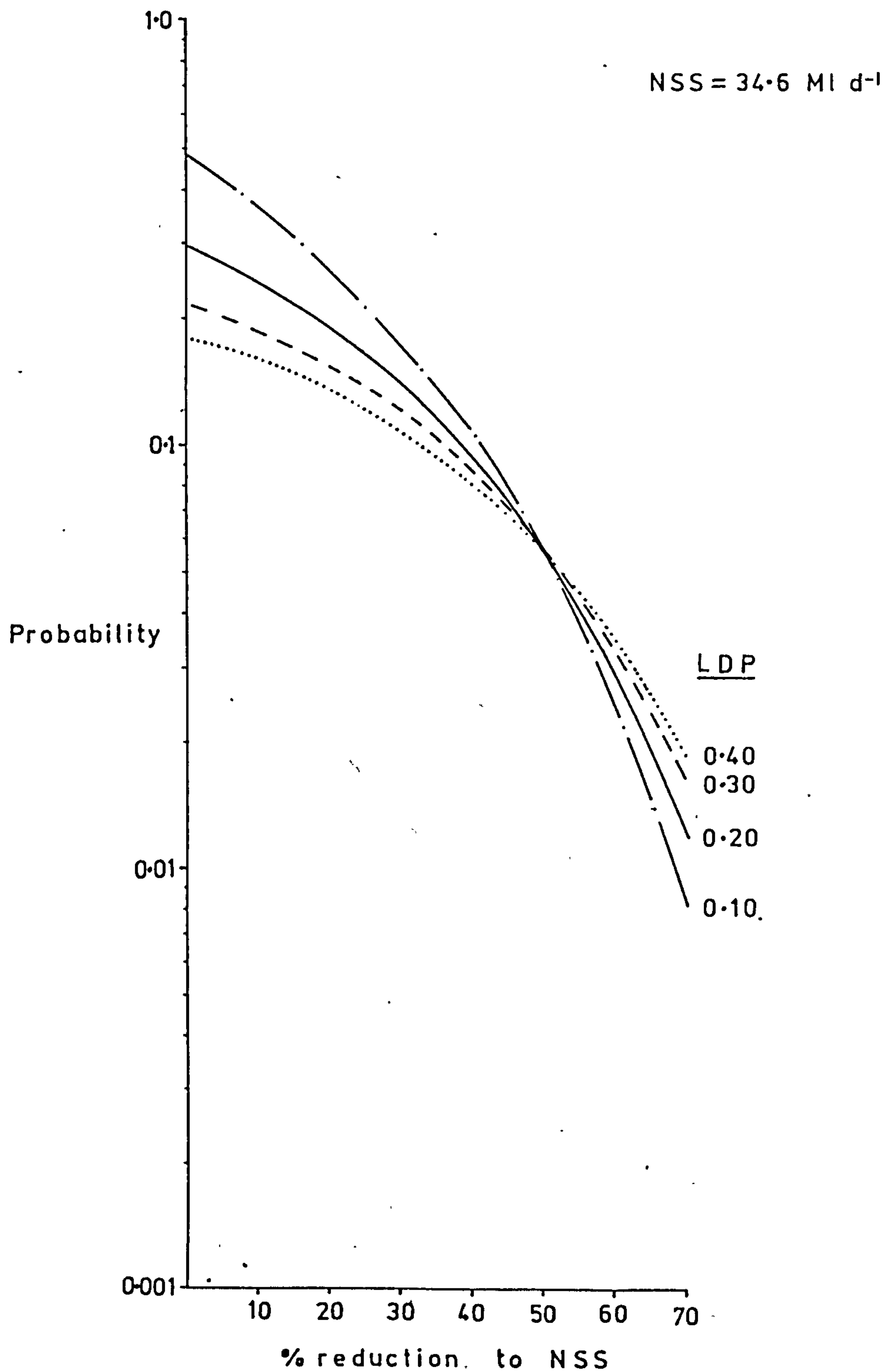
#### 5.5.2 The Effects of Varying LDP and NSS on the Incidence of Reductions to NSS

The absolute probabilities, in any NASN season, of given percentage reductions to a normal system supply rate of  $34.6 \text{ Ml d}^{-1}$ , for an LDP of 0.20, and some other values, is shown in graphical form in Fig. 5.16. As can be seen, the incidence of reductions in consumption of up to 50% is relatively lower for larger LDP values, and higher for reductions greater than half.

The probability of a 50% reduction is precisely the same for each different LDP value. Although this is indeed the case for any given NSS value, the reason behind this phenomenon has not been detected.

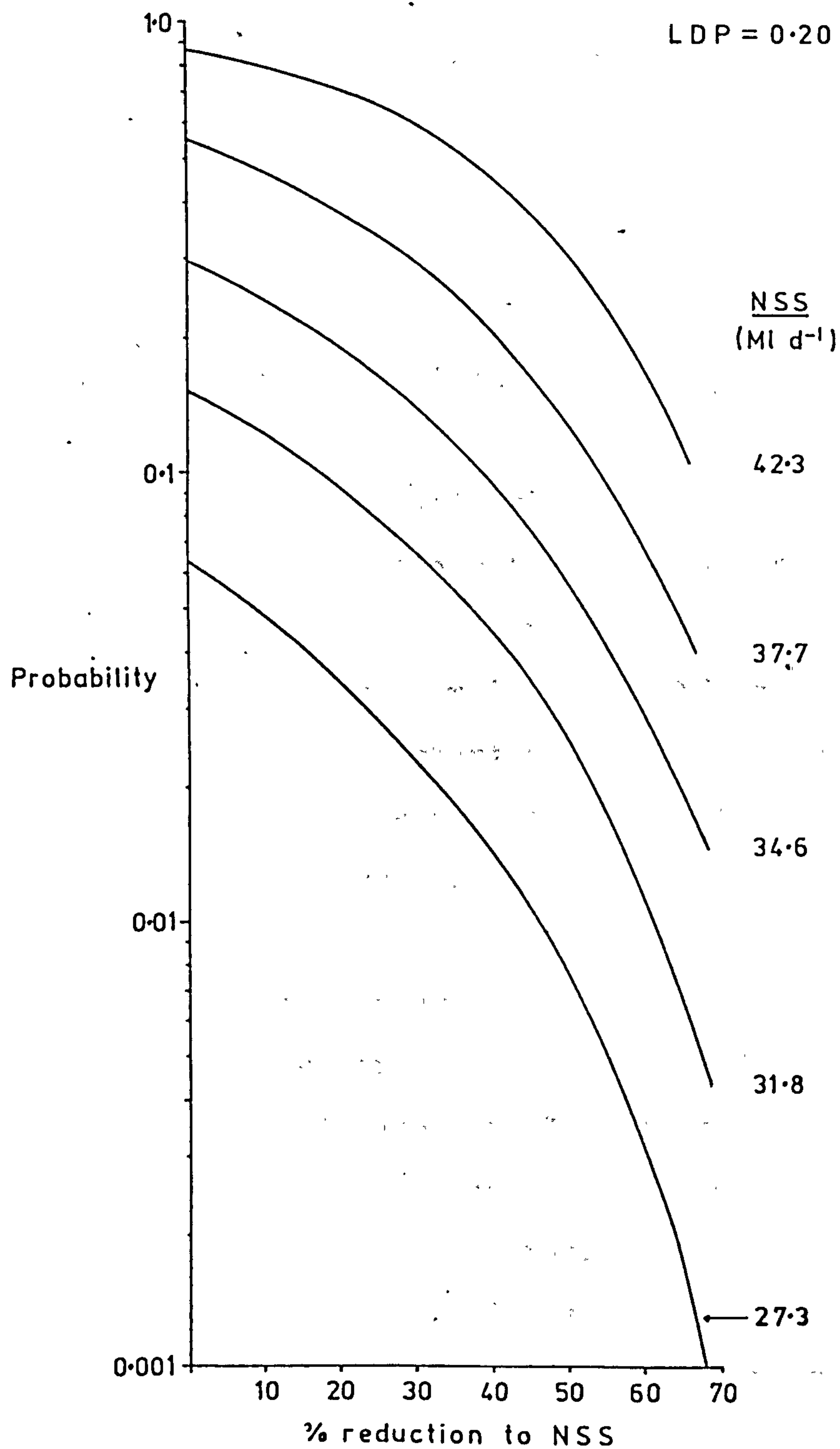
To allow some comparison between the incidence of reductions to different NSS rates, Fig. 5.17 can be used. The curves illustrated are those corresponding to a limiting deficiency probability of 0.20, for each of the five NSS

FIGURE 5.16 : The Effect of Varying the LDP on the Annual Probabilities of Given Percentage Reductions to a Given NSS





**FIGURE 5.17 : The Effect of Varying the NSS on the Annual Probabilities of Given Percentage Reductions to NSS, Using a Constant LDP**



values considered so far. As an example of the range of probabilities involved, the probability of a 50% reduction at a normal system supply rate of  $42.3 \text{ Ml d}^{-1}$  is, at 0.295, over ten times greater than the corresponding probability of recurrence of 0.0255 at an NSS of  $31.8 \text{ Ml d}^{-1}$ . In general terms, this increased relative incidence of given percentage reductions at higher NSS values, is of greater proportions for the larger percentage reductions to NSS.

#### 5.5.3 Assessing the Desired Incidence of Water System Supply Reductions

A method of relating reservoir yield or NSS, and the probability of necessary reductions to it (in accordance with a designated drought management policy) has been presented. However, in order to optimise the NSS and likely incidence of various levels of shortage for a given water supply system, it is first necessary to assess the desired recurrence probabilities of such shortfalls in system supply.

Very few attempts at solving this type of problem have been reported. One example is provided by Close et al (1970), who use a "shortage index" in a procedure to optimise reservoir yield and size. This index is defined as, the sum of the squares of annual ratios of shortage to demand over a 100-year period. For example, a shortage index of 0.25, which the authors consider to be "reasonable

for design purposes" would permit one hundred 5% shortages, or twenty 5% shortages and twenty 10% shortages, or one 50% shortage.

Despite its applicability to computer calculation, this approach has particular disadvantages. The first is that shortages are based over a whole year, and thus, the distribution of the severity of shortages within twelve month periods is ignored. Secondly, the rather contentious assumption is made that the effects of, and consequently the benefits to be gained from, a given annual shortage, are proportional to its square. For instance, it must be questioned as to whether a shortage of 5% every year for one hundred years can be considered as the equivalent of one 50% annual shortage over the same period.

Another optimisation study by Bargur and Gablinger (1972) considered the feasibility of "variable water supply policies". However, their work was confined to the supply operations, and not the "demand" part, of a water supply system in Israel.

The general lack of attention paid to this matter has been indicated by several authors, including Beran and Kitson (1977), who in assessing the drought of 1976 in England and Wales made the point that,

"the design of future water resource schemes must be tested on consumers, and that more research is needed into how this could be achieved".

As an indication of the type of information required, they go on to ask, if for example, consumers would prefer



to have minor restrictions, such as hosepipe bans for 3 months, or severe restrictions and rationing by stand-pipes in the street for only 3 weeks. In addition to this choice of drought management policy, consumers should also be consulted as to how often they would tolerate such measures, and if they would be prepared to pay more, or less for their water supply, to achieve<sup>ie</sup> this tolerable level.

#### 5.5.4 Derivation of Hypothetical Criteria for Desired Probabilities of Reductions to NSS

In the absence of any readily available information concerning consumer preferences and tolerances of water supply shortage, it is necessary to derive a sample set of such criteria to be used as a basis for an example illustrating the optimisation of the modelled water supply system.

A hypothetical series of supply shortage values and their associated probabilities has been derived in the following manner. Use has been made of Lothian Region Council's drought management policy (shown in Fig. 4.3) for the Edinburgh and Midlothian area, which is partially supplied by Gladhouse Reservoir. Using records of actual storage levels over the 92-year period of operation of the said reservoir, the associated incidence of actions necessitated by the above drought management plan have been gauged.

Actual reductions to NSS involved with each distinct action in the above contingency plan have been estimated from actual changes in normal system supplies recorded during the 1972/73 and 1959 droughts. The relevant information is detailed in Section 4.4, and summarised in Table 4.3.

The resulting figures, summarised in Table 5.3, fulfill the objective of providing a somewhat hypothetical set of tolerances to reductions to NSS (whose applicability is subject to that of the above drought management policy). They also allow a direct assessment to be made of the compatibility of the Lothian Region Council's drought management plan, and the official reliable yield of Gladhouse Reservoir (assuming that the new type of drought management policy presented is considered desirable). This is possible since such yields can now be associated with given incidences of various levels of reductions made to them, under the type of drought management presented in Section 5.4.

The cumulative reductions and probability values shown in Table 5.3, when plotted give the curves illustrated in Fig. 5.18. It is worth noting that the curve applying to consumer shortage is different to that which includes all drought management measures of both reducing consumption and increasing supply. This latter curve is that used to produce estimates of probabilities of reductions to NSS, in steps of 10%, necessary for the following optimisation procedure, since it includes all necessary alterations made to NSS.

TABLE 5.3 : Expected Annual Probabilities of Given Drought Management Measures in Any NASN Season for Gladhouse Reservoir : Based on the Lothian Region Drought Management Plan

Lothian Region measure (see Fig.4.3)	Affects: supply of consumpt.	Reduction to N.S.S. (%)	Cum. total reduction (%)	Cum. consumer reduction (%)	No. of Occas-sions in 92 years	Proba-bility
1	consumpt.	2	2	2	11	0.120
2	consumpt.	7	9	9	8	0.087
3	supply	11	20	9	6	0.065
4	consumpt.	9	29	18	5	0.054
5	consumpt.	21	50	39	2	0.022
6	consumpt.	33	62	51	0	0.010

TABLE 5.4 : Annual Probabilities of Given Percentage Reductions to Consumption and NSS in Any NASN Season for Gladhouse Reservoir: Based on the Lothian Region Drought Management Plan

Percent Reduction	0	10	20	30	40	50	60
Probability for consumer reduction	0.13	0.084	0.051	0.034	0.021	0.011	-
Probability for NSS reduction	0.13	0.084	0.065	0.052	0.037	0.022	0.011



**FIGURE 5.18 : Hypothetical Curves of Desired Annual Probabilities of Given Percentage Reductions to NSS : Based on the Lothian Region Drought Management Plan and 92 Years of Record for Gladhouse Reservoir**

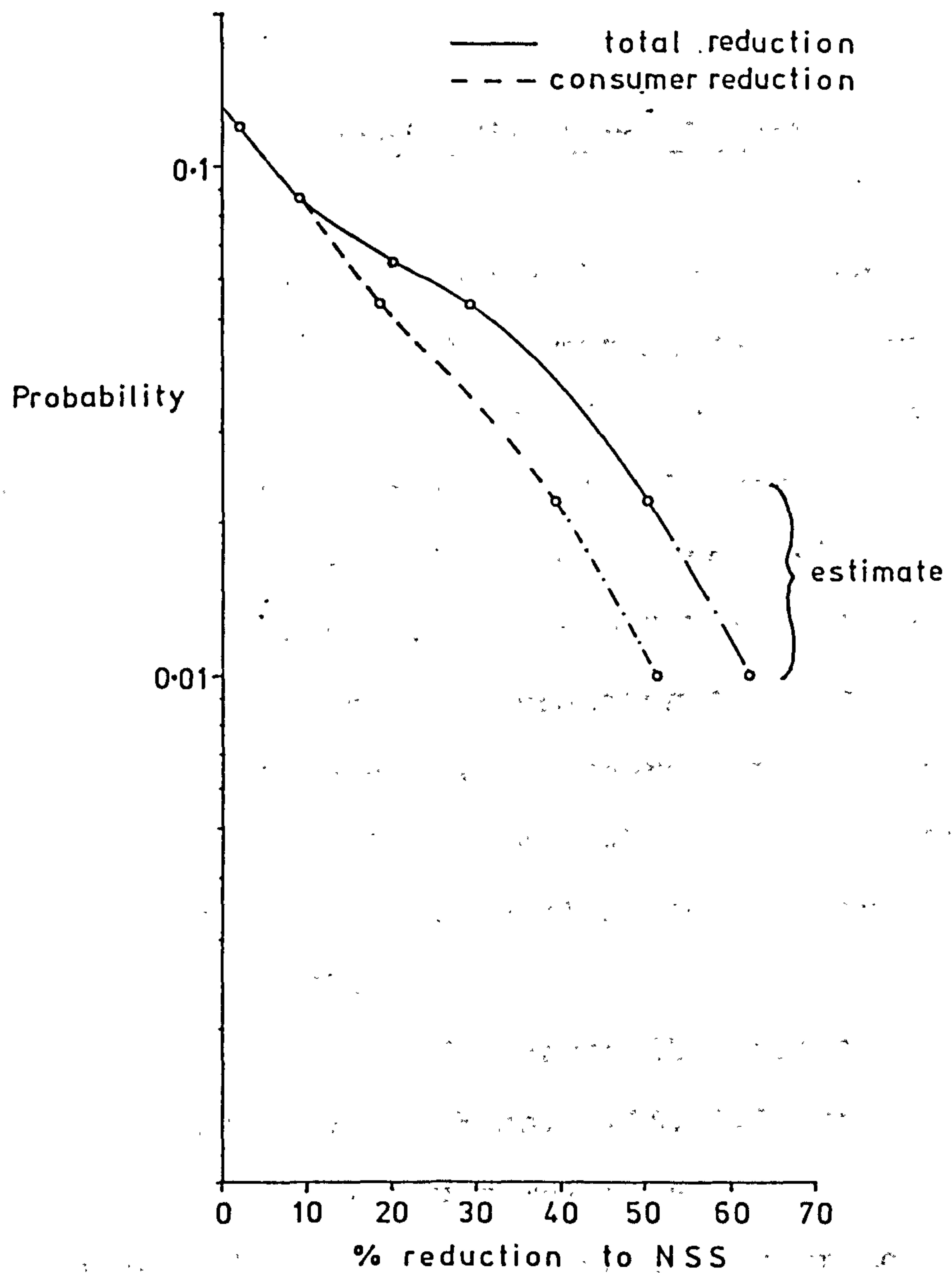


Table 5.4 shows the estimated probabilities for both consumer reductions and total reductions to NSS, in steps of 10% of NSS, derived from the curves on Fig. 5.18. The bottom row, representing a hypothetical example of the desired flexibility of NSS, can now be used to illustrate the adopted procedure for maximising NSS (or reliable yield).

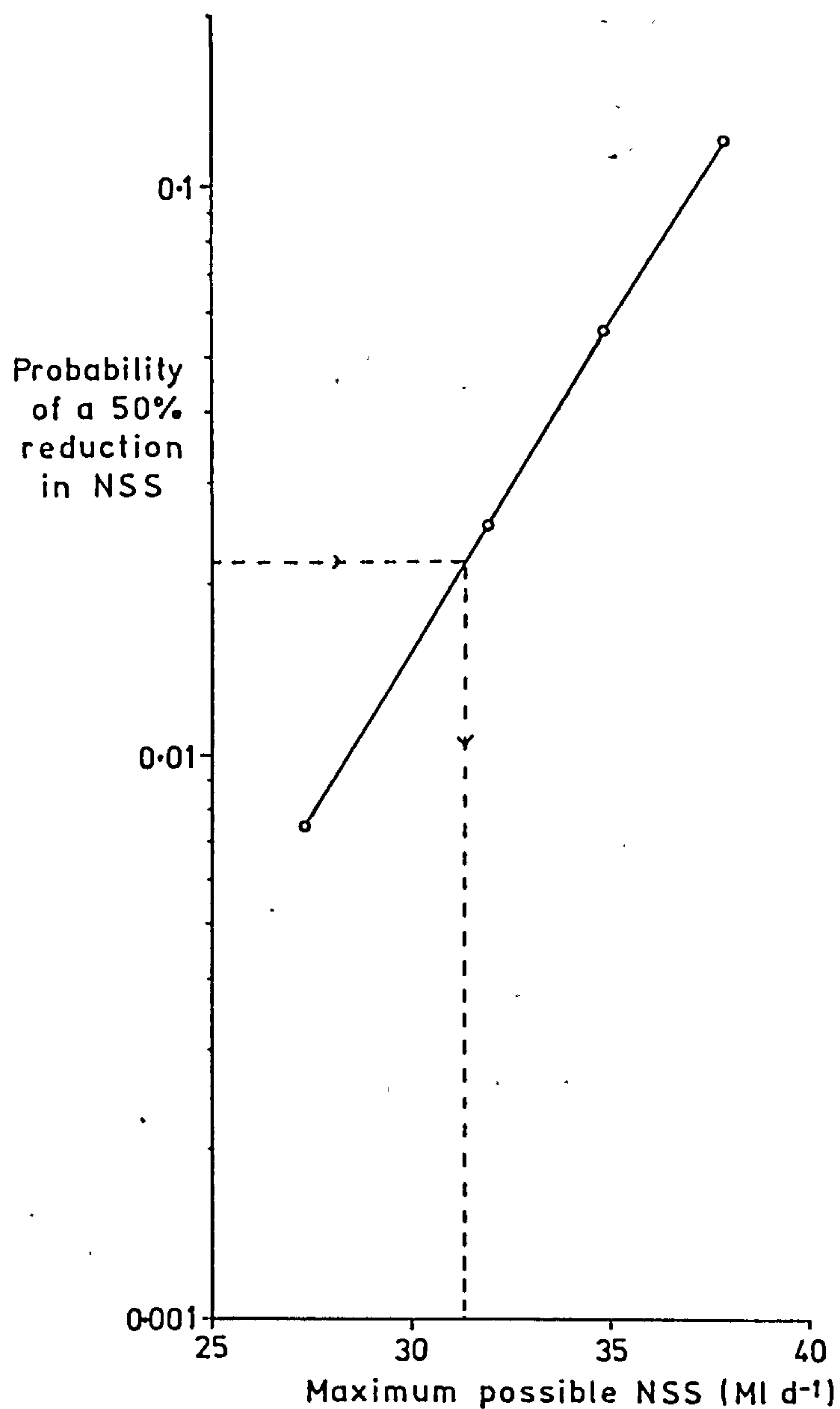
#### 5.5.5 Optimisation of Reservoir Yield and Drought Management Policy

The first step in this procedure is facilitated by the fact that, irrespective of the limiting deficiency probability value used, each sampled NSS has a discrete 50% reduction probability. As Fig. 5.19 illustrates, the maximum possible NSS associated with the desired 50% reduction probability of 0.022 (from Table 5.4) is  $31.2 \text{ Ml d}^{-1}$ . A limiting line corresponding to this value is included in Fig. 5.20, along with others representing the limiting NSS values and LDP levels which fulfill the remaining criteria on Table 5.4, relating to all percentage reductions to NSS up to 60%.

Fig. 5.20 uses curves of NSS versus LDP, plotted from data such as that shown in Figs. 5.15, 5.16 and 5.17, to represent the lowest LDP values which satisfy the required incidences of various reduction levels up to 50%, and the highest LDP values for reductions of over 50%.

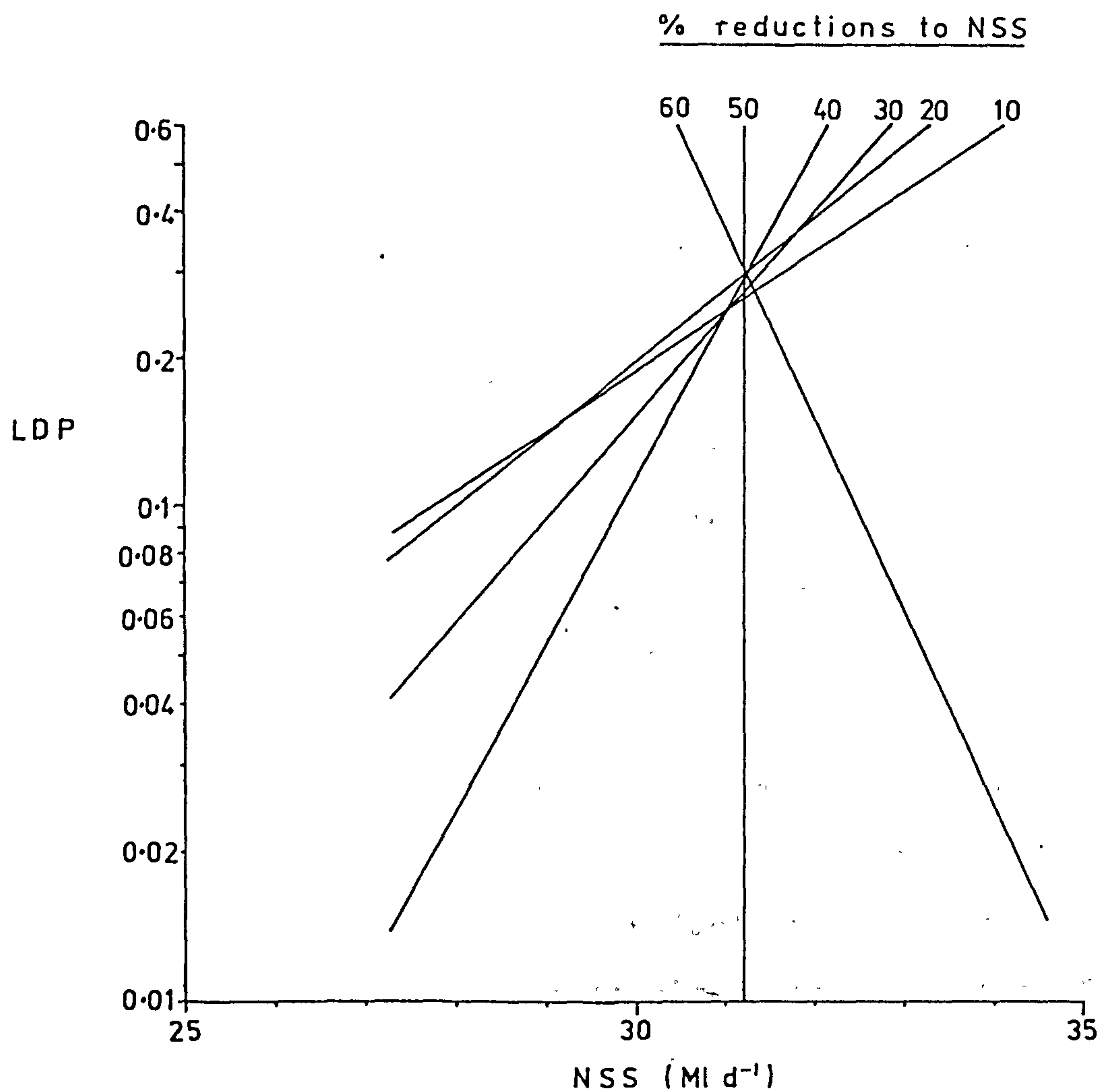
all for given rates of NSS.

FIGURE 5.19 : The Relation Between NSS and the Annual Probability of a 50% Reduction to it, for Gladhouse Reservoir





**FIGURE 5.20 : The Use of Linear Programming to Optimise LDP and NSS for the Adopted Sample Criteria Relating to the "Desired" Incidence of Given Percentage Reductions to NSS**

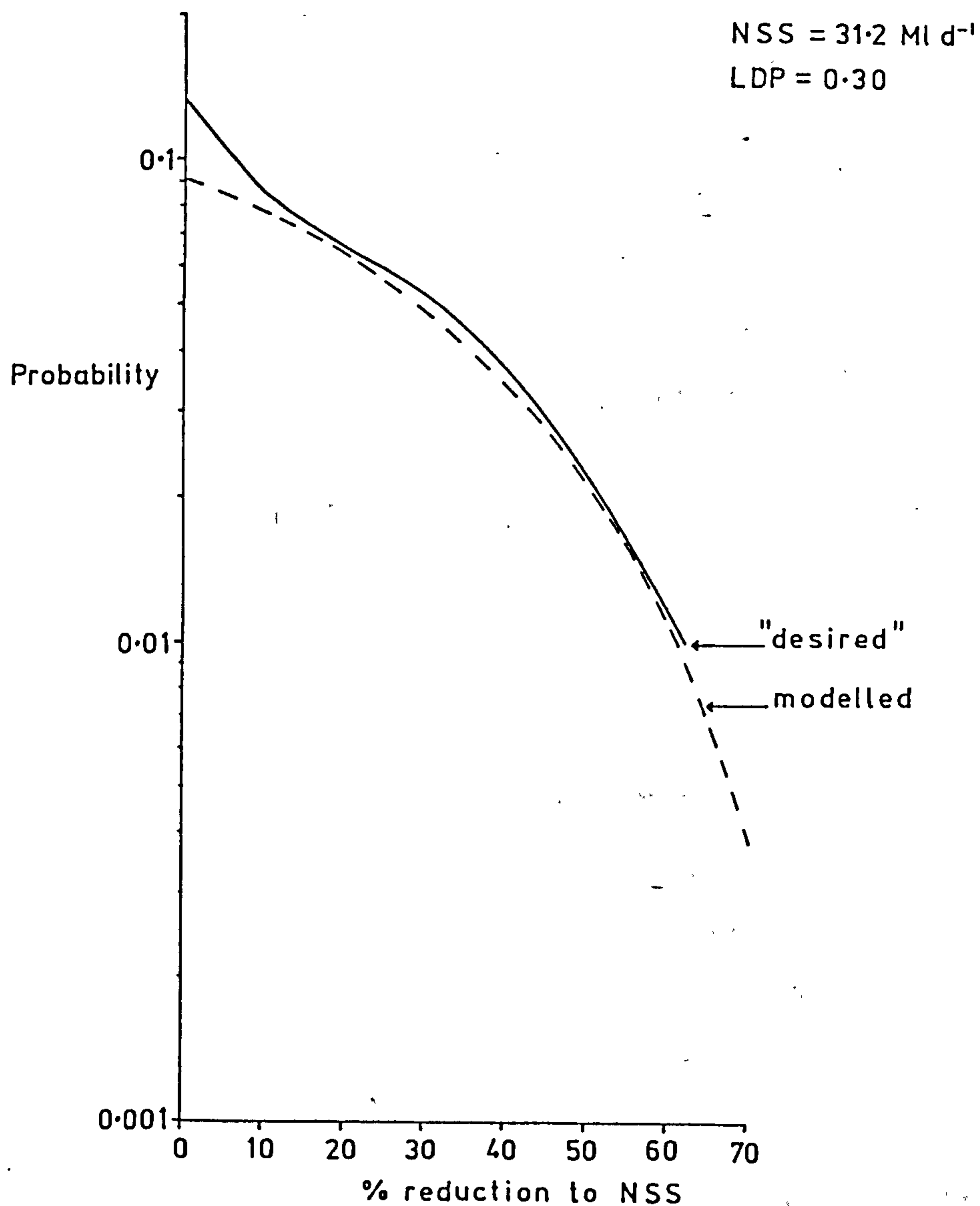


Three equally limiting curves can be identified, corresponding to reductions to NSS of 60%, 50% and 20%. At the maximum possible NSS of  $31.2 \text{ Ml d}^{-1}$  determined by the desired 50% reduction probability, an LDP of less than or equal to 0.30 is defined by the 60% reduction curve, and one of greater than or equal to 0.30 is required by the conditions of the curve representing a 20% reduction. Therefore, in this example a clearly defined drought management policy corresponding to use of a limiting deficiency probability of 0.30, is required at the optimal NSS of  $31.2 \text{ Ml d}^{-1}$ .

As Fig. 5.21 illustrates, the modelled expectancy of the three above levels of reduction to a normal system supply rate of  $31.2 \text{ Ml d}^{-1}$  is the same as the "desired" probabilities derived from the Lothian Regional Council's drought management plan. Comparison of the two curves on Fig. 5.21 reveals that a series of annual probabilities of reduction to normal system supply has been derived, which very closely resembles the sample of "desired" expectancies. In fact, only for reductions of less than 10% of NSS, do the derived and "desired" probabilities of occurrence differ to a notable extent.

Therefore, using the sample set of criteria relating to the tolerable probabilities of occurrence of reductions to the NSS ranging from 0 to 60% (shown in Table 5.4) to define the desired reliability of reservoir yield, the "reliable yield" of Gladhouse Reservoir can be said to be  $31.2 \text{ Ml d}^{-1}$ . The fact that this value is some 10% less

FIGURE 5.21 : Comparison of the "Desired" and Modelled Annual Probabilities of Given Percentage Reductions to NSS





than the revised official estimate of  $34.6 \text{ Ml d}^{-1}$  would indicate that (on the basis that the incidence of the implementation of the various steps in the Lothian Region drought management plan, over the 92 years of record at Gladhouse Reservoir, represents the desired probabilities of reductions to the normal system supply) this figure is not compatible with what could be taken to be the tolerable long term incidence of reductions to NSS (if the derived drought management plan is considered to be desirable).

If, of course, a different set of NSS reduction incidences was to be employed, then a reliable yield, and use of given LDP value, whose reliability related precisely to these criteria, could be derived in a similar manner.

#### 5.5.6 The Drought Management Policy Defined by the Optimisation Procedure

Any chosen reliable yield and desired incidence of deviations from it obtained by the foregoing method is, of course, dependent on a reservoir being managed along a given set of guidelines such as those described earlier.

In any impending shortage situation, information concerning initial (winter maximum) contents, present storage, the time taken for the present storage to be reached, and any savings made in NSS to date, could be fed into a computer programme such as that outlined in Fig. 5.11. Then, the required consumption necessary to conserve resources and avoid emptiness can be calculated on the basis of the limiting deficiency probability level being employed. As mentioned before, the inclusion of all the

above variables offers considerable flexibility to suit individual conditions, and thus strictly-defined operational rules are inappropriate. However, as an example of typical drought management procedures required under the above example, involving an NSS of  $31.2 \text{ Ml d}^{-1}$  and an LDP of 0.30, Fig. 5.22 provides information regarding the necessary reductions in NSS simulated for median NASN/duration conditions (such as those defined for an NSS of  $34.6 \text{ Ml d}^{-1}$  by curve III in Fig. 5.10).

The only subjective element included in this system of drought management, ie. that concerning the likely duration of forthcoming portions of NASN events, can in the above circumstances, be shown to produce almost negligible problems for the drought manager. As indicated earlier, the range of possible decisions he has to choose from is of significant proportions only when winter maximum contents are such that immediate reductions to NSS are required. Fig. 5.22 reveals that in this example, this is only necessary when an initial NASN state of 4 or less (ie. less 50% of maximum storage) occurs. In these circumstances, the probability of winter maximum contents being less than this value is 0.013. This indicates that the need for important subjective decisions concerning the NASN/duration relationship will be a somewhat rare occurrence.

NSS = 31.2 MI d<sup>-1</sup>  
 LDP = 0.30  
 NASN/duration curve III

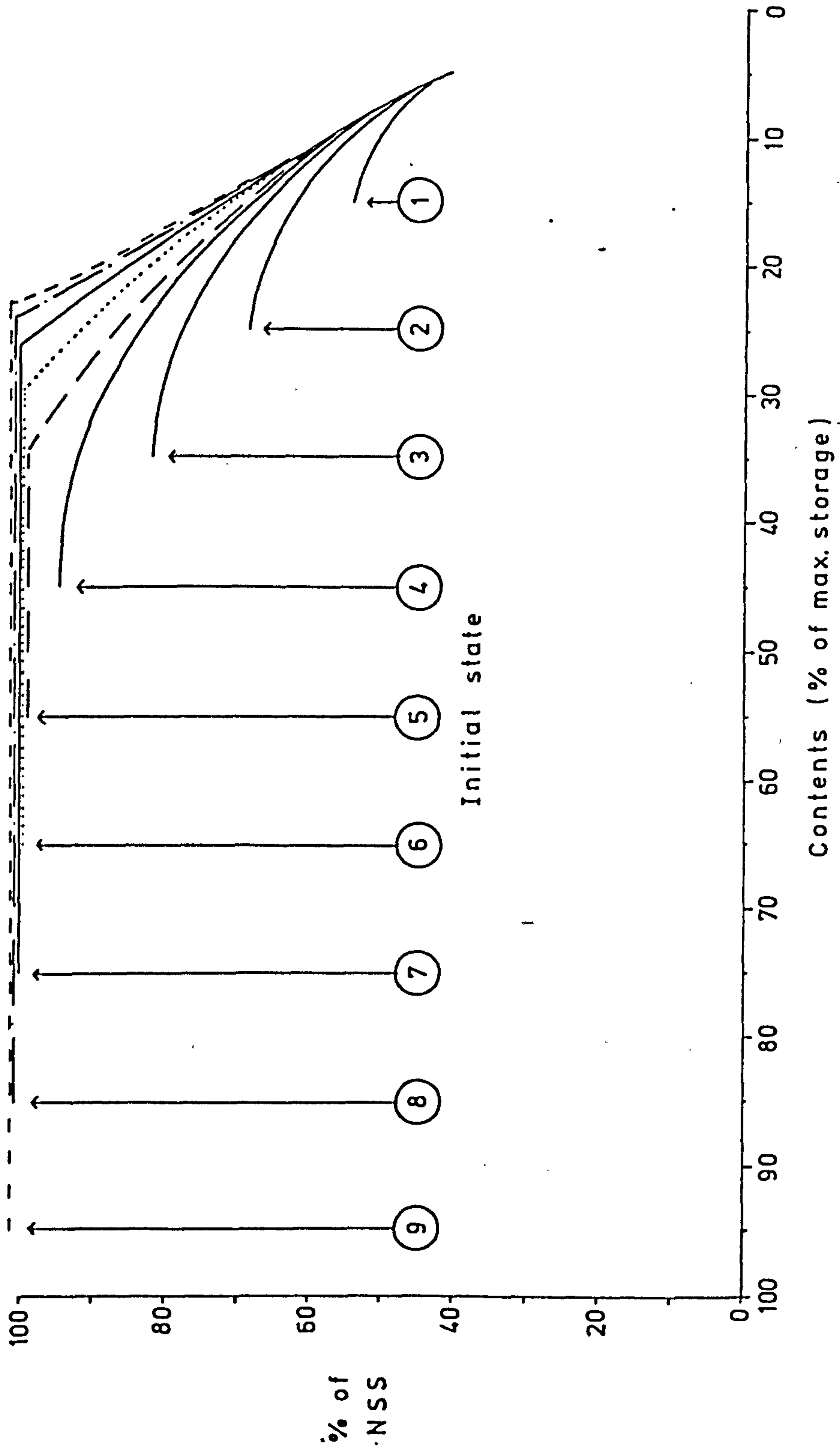


FIGURE 5.22 : Examples of Typical Drought Management Programmes Derived for Initial NASN States 1 to 9, for Given Standard Conditions



## 5.6 LIMITATIONS OF THE PROPOSED SYSTEM

Although the foregoing methodology, which includes an assessment of the tolerable incidences of various levels of imposed shortages of water supplied from impounding resevoirs, is considered to provide a much improved technique for defining and estimating "reliable yields", its limitations and shortcomings are numerous, and deserve mention.

Firstly, as is the general case, all methodologies for estimating future hydrological events have to be based on probability distributions referring to historical events. There is of course no guarantee that the events of the past, say, 100 years will closely resemble those of the next century. For example, it is clear from the Gladhouse run-off record shown on Fig. 2.19, that a reservoir yield based on, say, the earlier half of the 92-year period of record would be considerably different from that calculated using the latter half.

It would seem to be the case that the longer the period of record available, the more suitable it is. However, studies by Close et al (1970) and others, indicate that as record length increases above about 50 years, additional benefits derived become proportionately smaller. The period of record used, of 92 years would seem to be of an acceptable length. For instance, Yevjevich (1972) says of water resource decision making;

"most water resource specialists would agree that 80

to 100 years of data on a hydrological random variable would give sufficient information".

More specific limiting assumptions made in the simple probability theory of reservoirs, used as a basis for the derived methodology, are summarised by Lloyd and Odoom (1964). These are as follows;

- (i) time is discrete, not continuous as in reality;
- (ii) withdrawals are considered to be instantaneous, with one withdrawal in each time unit;
- (iii) inflows during non-overlapping time intervals are considered to be mutually independent.

The findings of Section 5.3.5 have shown the third item to be irrelevant in the case studied, and the developments of the methodology presented can be considered to have at least partially overcome the first two conceptual limitations, both concerned with the lack of a measurement of time. However, there is still the shortcoming that although some concept of time is included in a given simulated NASN event, no account is taken of the variation of net inflow over the relevant period. Indeed, it is assumed to be constant, which is clearly involves a gross simplification, but as indicated earlier, would not seem to involve large errors.

Other sources of error can be associated with the simplification and division of continuous distributions such as those of NASN and NASN/duration values. Storage deficiencies based on NASN series, and originally quantified by discrete units, or states, of 10% of maximum storage



were apportioned with their maximum values. For example, in the case of deficiency state -1 (deficiency of 0 - 10%), the value of 10% was used.

Furthermore, in the case of the division of the NASN/duration relationship on Fig. 5.10 into four equally probable classes, the minimum value in each class was used in the simulation of NASN durations.

The effect of both of these simplifications is to involve a slight overestimate of the expected probabilities of given percentage reductions to the normal system supply. This is thought to be more desirable than the inclusion of any parameters which could possibly cause any underestimation of the incidence of such imposed alterations to NSS. Any errors involved could be reduced by utilising smaller class intervals for the division of continuous variables into discrete units.

One further drawback concerning the output of the model to simulate reservoir behaviour, is that the long term annual recurrence probabilities of given levels of reduction to NSS contain no element of duration. Perhaps with further detail paid to the time factor it would be possible to estimate the incidence of say the necessity of hosepipe bans, not only in terms of the number of years likely to be affected, but also in terms of the probable number of days or weeks of imposition.



## 5.7 APPLICATION AND SUITABILITY OF THE PROPOSED SYSTEM

The necessary information for the formulation of reservoir reliable yields and drought management policies, as presented in this thesis, is a daily or perhaps weekly run-off record, based on direct or indirect measurements. Harris (1965) suggests a minimum period of fifty years for this type of analysis, however a longer period would be more desirable. Perhaps synthetically extended series of run-off data would be particularly suited to this type of treatment.

As in the worked example, the foregoing methodology can be used to assess the likely occurrence of different degrees of normal system supply failure imposed by a defined drought management policy, and also to assess the reliable yield (which has a precisely defined reliability) of reservoir water supply systems. Most importantly perhaps, the technique presented allows a direct relationship between these two factors to be formed, and also a means of deriving compatible and optimal conditions for both.

Consumer preferences and tolerances, as regards the frequency and extent of reductions in public water supply, can be taken into account at two levels. As in the example, desired incidences of reductions to supply can be used to assess the reliable yield. Alternatively, if an NSS is already fixed and unchangeable, then at least consumer preferences can be sought as to which type of drought

management policy (determined by the limiting deficiency probability employed) is to be used.

Apart from its possible applications to existing water supply schemes, the procedure described could be applied to resources planned for development, providing hydrological data exist, or can be synthesised. Indeed, in such circumstances, an extra variable describing maximum reservoir storage could be included, thus allowing the optimisation of three parameters, ie. the reliable yield (or NSS), the probabilities of enforced alterations to it, and reservoir capacity.

SECTION 6

CONCLUSIONS



## 6 CONCLUSIONS

The subject of drought has been identified as one of global significance in the 1970's. However, drought tends to mean different things to different people in different parts of the world. For instance, the occurrence of drought in such a reputedly wet country as Scotland may be a difficult concept for some to accept. In order to clarify what is meant here by the term "drought", it has been necessary to derive a general definition, applicable to all situations. By defining drought as,

"a period of abnormal weather involving a lack of water to meet requirements"

it is possible to provide a universally applicable meaning. This definition has also provided a useful basis for the development of the structure of this thesis; ie. an assessment of "abnormality" is followed by others concerning water "supply" and "demand".

As regards the first of the above analyses, it can be concluded that the unusual hydrometeorological events of the 1971-76 period in Scotland definitely deserve "drought" status. For example, at Kinloss, in Moray in the north-east, the total precipitation for the year of 1972, at 345mm, represents only 54% of the 1941-70 annual average. Unusual as this is, it is of even more significance when it is noted that potential evaporation ( $E_p$ ) over the same year was 200mm greater, at 545mm (104% of the 1956-75 average). The facts that the deviation from the

average  $E_p$  value is relatively small, and that as indicated in Section 2, values of actual evaporation were typically much less than those of  $E_p$ , reveal the specific importance of such low rainfall values in relation to the quantities of water available as run-off. As an example, following two consecutive years when  $E_p$  totals exceeded those for rainfall, annual run-offs as low as 11mm (10% of average) were recorded in 1973 in East Lothian in the south-east of Scotland.

Extreme as such annual events were, in terms of recurrence probability, it appears that rainfall events over the three-year period 1971-73 were even more severe over most of eastern Scotland. The whole of this part of the country received less than 80% of the equivalent 1941-70 average precipitation over this period. The investigation of a 92-year series of rainfall and run-off, derived for the catchment area of Gladhouse Reservoir in Midlothian, indicates that the return periods of this three-year event are approximately 100 years for rainfall and 250 years for run-off.

This feature of the drought is of most significance in the field of public water supply from impounding reservoirs. The reliable yield of these supply systems is based on the estimated minimum three-year rainfall of 80% of average. Since over 90% of all public water is supplied from such sources in the south-east of Scotland, then widespread problems of failing to meet consumer demands might be expected. Such problems would be compounded by



the fact that the pattern of low flow spells was generally such that they terminated towards the beginning of winter, when reservoirs are usually recovering from their annual minimum level of contents.

It would appear that nature could not have produced a hydrologic drought any more likely to cause water supply problems in all areas of the East of Scotland. For, in the north-east, where the vast majority of public water supply systems involve negligible storage, and are thus dependent on the "run of the rivers", problems could also be anticipated because of the specific nature of the low river flows encountered. For instance, a new type of analysis of flow duration data has revealed that whereas on the R. Tyne at East Linton in the south-east, drought flows were most severe at the 20 percentile flow level, on the R. Deveron at Avochie in the north-east, the 1 percentile flow events in 1976 were the most abnormal annual feature during the 1971-76 period. The return period of the 58 consecutive days of flow less than this level has been estimated to be greater than 30 years.

In view of the importance of understanding the nature of such low flows for water management interests, it was felt desirable to develop maps of the study area depicting both 1 and 5 percentile areal run-off values. By collating and processing data for hundreds of "spot gaugings", it proved possible to construct comprehensive and detailed maps, which reveal a great variation in low flow yields, over the East of Scotland. In relation to the lowest yields,



extensive areas where 1 and 5 percentile yields are less than 0.5 and 1.0 l s<sup>-1</sup> km<sup>-2</sup> respectively, have been clearly identified. In small catchments confined to such areas, the particularly severe and persistent low flows of the 1970's were often associated with notable deteriorations in water quality caused by a lack of available water for adequate dilution of effluents. Such impacts have been detailed for the Leet Water in the lower Tweed basin, and the Peffer Burn West in East Lothian.

Similar drought impacts on larger river systems were, as above, generally confined to areas where water pollution was to some extent an ongoing feature. The various effects of the low flows during the period have been described in some depth in two case studies relating to the R. Don in the Grampian Region, and the R. Almond in the Lothians. It has been recognised that for a detailed analysis of drought impacts on the complete aquatic ecosystem affected by waste water disposal systems, adequate data are required in relation to both the "supply" and "demand" aspects of drought. As regards the first matter, the detailed study on the R. Almond has indicated that it is possible to produce a model which successfully predicts values for water quality parameters such as concentrations of D.O., NO<sub>2</sub> and PO<sub>4</sub>, using <sup>n</sup>inputs of flow, water temperature and an index of sunshine. However, there is a lack of available information concerning the second type of data above, ie. the specific requirements for the growth and development of aquatic life. This has rendered

impossible a total assessment of drought impacts related to that field of water management concerned with waste water disposal.

In the other sphere of water management considered in this thesis, ie. public water provision, it has been possible to investigate drought impacts more fully, using assessments of both water supply capability and relevant demands. The full range of impacts incurred over the 1971-76 period was not readily apparent to water consumers. Although hosepipe restrictions and publicity campaigns aimed at persuading the public to reduce their water consumption were frequent and widespread, incidences of severer forms of water rationing were rare. These were restricted to the remote rural areas of the north-east, where water supplies had to be transported temporarily by road, in 1971, 72, 73 and 76. In place of severe rationing of water availability, potential supply failures were averted by transferring supply sources, using emergency sources, and reducing reservoir compensation outflows; such measures often requiring the issue of an Emergency Order from the Secretary of State for Scotland. These actions could possibly be expected to exacerbate the effect of the droughty river flows on the natural environment, but this was not the general case. Whereas emergency river abstractions in the north-east typically made negligible reductions to flow in affected watercourses, the reduced reservoir compensation flows in the south-east had more severe effects in some streams.

The range and proliferation of the above drought impacts associated with activities of water supply agencies



in Scotland, has, of course, raised questions as to the actual and the desired reliability of supply sources, especially impounding reservoirs. Detailed investigation has indicated the inconsistencies and inappropriateness of the accepted procedure for estimating the reliable yields of such sources. Many reservoirs failed to fulfill their supply function during the 1971-76 period, and what saved Water Boards and consumers from excessive shortages was the large short term flexibility of water demand, and especially supply. For instance, directly enforceable demand management measures (hosepipe ban and publicity) can achieve a maximum saving in consumption of around 12%. However, further total savings of around 20 to 100% of the normal system supply are possible by implementing the use of alternative supply sources. This supply flexibility tends to be lowest in the more populous lowland areas. For example, for the Edinburgh and Midlothian supply area, it was only 17.7% of the normal system supply over the 1971-76 period. In areas so highly dependent upon impounding reservoirs, drought management problems were perhaps the greatest.

There is some evidence of a lack of directly available powers which would allow water authorities more scope in the area of demand management during a drought. It is considered that the legal provisions of the Drought Act of 1976 applying to England and Wales, would have been much appreciated by Water Boards, if not consumers, in Scotland over the 1971-76 period. In addition, it could be argued



that the events of this period caught these Boards rather unprepared, and that contingency plans for drought management were somewhat lacking. The actions of some Boards would certainly indicate the need for a more organised and rational approach to drought management. Such policies as were used, whilst providing a logical series of rationing procedures for use of available supplies in reservoirs, took little account of the circumstances preceding critical storage situations, or developments likely to follow them. Such shortcomings in the drought management schemes used for reservoir resources provided the reason for the formulation of an alternative system of management.

The method developed includes consideration of the events during a reservoir depletion season leading up to a critical storage situation, and the probability of different levels of storage deficiency at the end of this season, to calculate reductions to the normal system supply necessary to avoid a given potential storage deficiency. For any chosen limiting deficiency probability (the factor which determines the nature of a drought management programme) a rationalised series of measures, whereby successively more severe restrictions on water use are applied as reservoir contents continue to decline, can be formed. The sequence of restrictions is designed to prevent reservoir contents ever reaching zero.

The frequency of such restrictions necessary over the long term can then be compared with the desired

incidence at all levels of reduction, and then both the reservoir yield and drought management policy mutually optimised. In this way, the precise reliability of a reliable yield is known, as it corresponds to the desired incidence of given levels of reduction to the normal system supply. A worked example, concerning Gladhouse Reservoir in Midlothian, has shown this to be a useful procedure for assessing the optimal yield and associated drought management contingency plan, for an existing water supply reservoir. In addition, this system can be applied to new and proposed sources, thus allowing the optimisation of three variables, ie, reservoir yield, its reliability expressed as the likely incidence of necessary reductions made to it, and reservoir capacity.

In the above circumstance, the requirement of a long run-off record for this procedure could pose problems, but the techniques involved lend themselves to the use of synthetic run-off series, thus somewhat reducing this difficulty. Despite the major obstacle of obtaining sufficiently long run-off records, and the degree of complexity involved in this proposed system for reservoir drought management and reliable yield formulation, it is considered that these drawbacks are outweighed by its advantages. Namely, it makes use of run-off values over time periods relevant to drought events; it offers a choice of drought management plans which can be applied with confidence, and a knowledge of well-defined probabilities of deficiency in storage; it allows a precise reliable yield to be obtained which is directly related to the desired



incidence of deviations made from it; and economic or other criteria can be applied to optimise all relevant variables involved in water supply planning.

It could be argued that the methodology presented in this thesis could be considered to be too complex and involved for use in present times. However, particularly in countries where the balance between the scope for water supply capability and water demands is rather delicate, such a system could be both useful and economically justified. Indeed, the desirability and necessity of improved methods of water resource planning and management in relation to drought will probably increase in the future. As pointed out in the Introduction, a continuation of the pressures of both increasing populations and per capita water demands would make potential drought problems, and the need to be fully prepared for them, much more serious in the future.

Therefore, there would appear to be ample scope for the further development and application of the proposed system of drought management and reservoir reliable yield formulation, in the sphere of water resource planning and management.



## BIBLIOGRAPHY

- Aberdeen Press and Journal : 27.7.71 to 1.11.71;  
2.9.72 to 29.11.72; 7.9.73 to 11.10.73.
- Almond Angling Association, 1980 : personal  
communication.
- Anderson, I. E., 1961 : Errors in streamflow measurement.  
In United States Geological Survey, Prof. Paper  
424-C, pp. 37-39.
- Arbroath Herald and Angus County Advertiser : 3.11.72;  
30.4.73 to 22.6.73; 12.7.76 to 27.8.76.
- Baldwin - Wiseman, W. R., 1941 : Further cartographic  
Studies of drought. Quart. J. Roy, Met. Soc.  
67 (288), pp. 39-47.
- Bargur, J., and Gablinger, M., 1972 : The hydrological  
feasibility of variable water supply policies.  
In Decisions with inadequate hydrologic data.  
Proc. 2<sup>nd</sup> Int. Symp. in Hydrology, Fort Collins,  
Colorado, U.S.A., pp. 252-265.
- Bartsch, A. F., 1948 : Biological aspects of stream  
pollution. Sewage Works Jnl., 20, pp. 292-302.

Bates, C. G., 1935 : Climatic characteristics of the Plains Region. In Possibilities of Shelterbelt Planting in the Plains Region, by M. Silcox, F. A., et al., Washington, D. C.

Beran, M. A., and Kitson, T. , 1977 : Assessing the severity of the 1976 river flows - a hydrologist's and water resource planner's viewpoints. Proc. Instn. Civ. Engrs. Part 1., 62, pp. 529-533.

Berwickshire News and East Lothian Advertiser : 23.1.73 to 1.12.73.

Binnie, A., 1892 : On mean or average annual rainfall, and the fluctuations to which it is subject. Proc. Inst. Civ. Engrs., 109, Part iii.

Blairgowrie Advertiser : 28.7.72 ; 20.8.76.

Boulton, A. G., 1965 : Minimum Acceptable flow. Jnl. Instn. of Water Engrs., 19, pp.59-80.

British Rainfall Organisation, 1936 : British Rainfall. Air Ministry, Met. Office, London.

Brooks, C.E.P., and Glasspoole, J., 1928 : British droughts and floods. Ernest Benn Ltd., London.

Caithness Courier : 1.9.76 to 27.10.76.

Central Water Planning Unit, 1977 : The 1975 - 76  
drought - a hydrological review. Technical  
note No. 17.

Chang, M., and Boyer, D. G., 1977 : Estimates of  
low flows using watershed and climatic  
parameters. Wat. Res. Research, 13, pp.997-1001.

Clarke, R. T., and Newson, M. D., 1978 : Some  
detailed water balance studies of research  
catchments. Proc. Roy. Soc. Lond. Ser. A.,  
363, pp. 21-42.

Close, E. R., Beard, L. R., Dawdy, D. R., 1970 : Objective  
determination of safety factor in reservoir  
design. Proc. Am. Soc. Civ. Engrs. (Hydraulics  
Division), 96, pp. 1167-1177.

Clyde River Purification Board; 1971 to 76:  
C.R.P.B. Annual Reports, C.R.P.B., East Kilbride.

Cole, H. S., 1933 : Droughts in Arkansas.  
Monthly Weather Review, 61 (s), pp. 129-140.



Cole, J. A., Gunawardane, G.J.P., and Jones, J., 1970 :  
Reservoir yield IV - generalised curves of  
probability of emptiness of a reservoir,  
obtained from a 2 season application of  
the Moran model, Water Research  
Association, Tech. Memorandum T. M. 60.

Commission of the European Communities, 1976 :  
Proposal for a council directive on the quality  
requirements for waters capable of supporting  
freshwater fish. COM (76) 401 final, Brussels.

Crann, H. H., 1977 : Lessons learnt. In The Drought  
of 1975 - 76. Proceedings of a  
seminar by the Instn. of Wat. Engrs. and  
Scientists, and the Instn. of Civ. Engrs.,  
29<sup>th</sup> March, 1977, London.

Dalkeith Advertiser : 9.11.72 to 31.1.74 ; 15.8.74; 9.9.76.

Davy, E. G., 1974 : Drought in West Africa.  
W.M.O. Bulletin 23, pp 18-23.

Doornkamp, J.C., Gregory, K.J., and Burns, A.S., 1980:  
Atlas of drought in Britain 1975 - 76.  
Inst. British Geographers, London.

Doudoroff, P., and Shumway, D. L., 1967 : Dissolved oxygen criteria for the protection of fish. Am. Fisheries Soc. Special Publication No. 4, pp. 13-19.

Downing, K. M., and Merkins, J. C., 1957 : The influence of temperature on the survival of several species of fish in low tensions of dissolved oxygen. Ann. Appl. Biol., 45, pp.261-267.

Drought Act, 1976 : H.M.S.O., London.

Dundee Courier and Advertiser : 21.8.76.

Dundee Evening Telegraph : 20.9.73.

East Lothian Courier : 30.7.76 to 10.9.76.

Edinburgh and District Waterworks Act, 1874.

Edinburgh Evening News : 16.5.80.

East Lothian News : 14.9.73 ; 10.9.76.

East of Scotland College of Agriculture, 1977a : Profitability of farming in South - east Scotland 1975 - 76. E.S.C.A. Bulletin No. 20.

East of Scotland College of Agriculture, 1977b:

Fertiliser recommendations - revised edition.

E.S.C.A. Bulletin No. 18.

European Inland Fisheries Advisory Commission, 1973:

Report on dissolved oxygen and inland

fisheries. E.I.F.A.C. Technical Paper No. 19,

pp. 10, F.A.O., Rome.

Fife and Kinross Water Board : 1971 to 1974. F.&K.W.B.

Minutes of meetings.

Fife Free Press : 11.7.75 to 10.10.75.

Fife Herald and Journal : 11.10.72; 9.5.73 to 4.7.73.

Fisher, R. A., and Yates, F., 1963 : Statistical tables,

6th edition, Table VII. Longmans, London.

Foley, J. C., 1957 : Droughts in Australia - review of

records from earliest years of settlement

to 1955. Australian Bureau of Met.,

Bulletin No. 43, pp.281.

Food and Agriculture Organisation of the United Nations,

1969 : Water pollution. F.A.O. Fisheries

Technical Paper No. 94., Rome.



Forth River Purification Board, 1970 - 1977 : F.R.P.B.

Annual Reports, F.R.P.B., Edinburgh.

Forth River Purification Board, 1980 : personal  
communication.

Gibbs, W. JI, 1975 : Drought - its definition,  
delineation and effects. In W.M.O. Special  
Environmental Report No. 5., W.M.O. publn.  
No 403, Geneva Switzerland.

Gibbs, W. J., and Maher, J. V., 1967 : Rainfall deciles  
as drought indicators. Bureau of Meteorology,  
Melbourne, Australia.  
Bull. No. 48, 33 pp.

Glasspoole, J., 1924 : Fluctuations of annual rainfall  
three driest consecutive years. Trans. Instn.  
Water Engnrs, 29, pp. 83-101.

Gould, B. W., 1961 : Statistical methods for estimating  
the design capacity of dams. Jnl. Inst.  
Engs. Australia, 33, p.405.

Grindley, J., 1967 : The estimation of soil moisture  
deficits. Met. Mag., 96, pp. 97-108.

Hardison, C. H., and Martin, R.O.R., 1963 : Water supply  
characteristics of streams in the Delaware  
River basin and in southern New Jersey. U.S.  
Geol. Survey Water-Supply Paper 1669-N, 45pp.

Hare, F. K., 1977 : Is the climate changing?

Mazingira, 1, pp. 18-29.

Harris, R. A., 1965 : Probability of reservoir yield failure using Moran's steady state probability method and Gould's probability routing method.  
Jnl. Instn. Water Engnrs, 19, pp.302-328.

Hay, R.F.M., 1974 : Climatic change past and present.  
Span, 17 (part 3), pp. 104-105.

Highland News : 12.8.76 to 2.9.76.

Highland Regional Council, 1978 : personal communication.

Hoyle, N., 1963 : Frequency curves and applications.  
Jnl. Instn. Water Engnrs., 17, pp. 499-519.

Hoyt, J. C., 1936 : Droughts of 1930 - 1934. U.S.  
Geol. Survey, Water Supply Paper No. 680, 106pp.

Hunt, O. P., 1963 : Use of low flow measurements to estimate flow duration curves. In U.S.  
Geol. Survey, Prof. Paper 475-C, pp.176-197.

Huntingdon, R., 1977 : 1976 water supply problems - action taken, Knowledge gained. Public Health Engr., 5 (No. 5), pp. 109-115.

- Huschke, R. E. (Ed.), 1959 : Glossary of American Meterology.  
Amer. Met. Soc., Boston, Mass., 638pp. ....
- Hynes, H.B.N., 1963 : The Biology of Polluted Waters.  
Liverpool Univ. Press, 202pp.
- Institute of Hydrology, 1978 : Low Flow Studies Report.  
Institute of Hydrology, Crowmarsh Gifford, Oxon.
- Institution of Water Engineers and Scientists and the  
Institution of Civil Engineers, 1977 :  
Proceedings of a seminar on The Drought  
of 1975 - 76, Chameleon Press, London.
- Kelley, T. L., 1924 : Statistical Method. MacMillan,  
New York.
- Lamb, H. H., 1966 : The Changing Climate.  
Methuen, London.
- Landsbørg<sup>e</sup>, H. E., 1975 : Drought, a recurrent element  
of climate. In W.M.O. Special Environmental  
Report No 5, W.M.O. publ. No. 403, Geneva,  
Switzerland.
- Lang, R., 1915 : (in German) reported by W.M.O.  
Special Environmental Report No 5., W.M.O.  
publ. No. 403, Geneva, Switzerland.



Ledger, D. C., and Thom, A. S., 1977 : 200 years of potential moisture deficit in South - East Scotland. Weather, 32 , pp. 342-349.

Lillicrap, R. J., 1977 : Meeting the problems. In The Drought of 1975-76. Proceedings of a seminar by the Instn. of Wat. Engrs. and Scientists and the Instn. of Civ. Engrs., 29th March, 1977, London.

Lloyd, E. H., 1963 : A probability theory of reservoirs with serially correlated inputs. Jnl. of Hydrology, 1, pp.99-128.

Lloyd, E. H., 1970 : Transient and asymptotic behaviour of reservoirs with non-persistent seasonal inflows. Jnl. of Hydrology, 10, pp. 243-258.

Lloyd, E. H., and Odoom, S., 1964 : Probability theory of reservoirs with seasonal input. Jnl. of Hydrology, 2, pp. 1-10.

Lothian Region Water and Drainage Committee :  
Minutes for meeting on 6.9.76.

Lothian Region Water Supply Services, 1980 :  
personal communication.

Maher, J. V., 1968 : Drought assessment by statistical analysis of rainfall. Proc. of the W.M.O. Seminar on Agricultural Meteorology, Bureau of Meteorology, Melbourne, Australia.

Meaden, G. T., 1976 : North - West Europe's great drought. Jnl. Met., 33, pp. 379-383.

Meteorological Office, 1977 : Monthly Weather Reports, VOL. 93, Nos. 7 & 8. H.M.S.O.

Meteorological Office, 1979 : personal communication.

Meteorological Office, 1980 : Monthly and Annual Totals of Rainfall 1972 for the United Kingdom. Met. 0.940, Met. Office, Bracknell, Berks.

Ministry of Agriculture, Food and Fisheries, 1967: Potential Transpiration. M.A.F.F. Tech. Bull. No. 16. H.M.S.O.

Moran, P.A.P., 1954 : A probability theory of dams and storage systems. Aust. Jnl. App. Sci., 5, p116.

Moran, P.A.P., 1959 : The Theory of Storage.

Methuen Ltd., London.

Murray, R., 1977 : The 1975 - 76 drought over  
the U. K. - hydrometeorological aspects.  
Met. Mag., 106, pp.129-145.

Musgrave, D. C., 1977 : Government Action. In The  
Drought of 1975-76. Proceedings of a  
seminar by the Instn. of Wat. Engrs. and  
Scientists and the Instn. of Civ. Engrs.,  
29th March, 1977, London.

Nairnshire Telegraph : 24.8.76.

Newson, M. D., 1978 : The Effects of the Drought on  
Water Balances of Experimental Catchments  
With Particular Reference to Upland Wales.  
Institute of Hydrology (Plynlim<sup>o</sup>n),  
Llanbrynmair, Powys.

North East River Purification Board, 1976 & 77 :  
N.E.R.P.B. Annual Reports. N.E.R.P.B.,  
Aberdeen.

North East River Purification Board, 1980 :  
personal communication.



Northern Scot : 23.7.71 to 10.11.72 ; 15.8.73 to 28.1.74;  
19.8.74; 14.7.75 to 6.10.75; 10.7.76 to 25.10.76.

Nottinghamshire Algorithm Unit, 1977 : Curve and surface  
fitting. Chapter E02ACF, N.A.G. Fortran  
Library Manual, Mark 6.

Owens, M., and Edwards, R. W., 1964 : A chemical  
survey of some English rivers. Proc. Soc.  
for Water Treatment and Examination, 13,  
pp. 134-144.

Palmer, W. C., 1965 : Meteorological drought.  
U. S. Weather Bureau, Washington, D. C.,  
Research Paper No. 45, 58pp.

Pearson, K., 1895 : Skew variation in homogeneous  
material. Phil. Trans. Roy. Soc. London,  
Series A, 186, pp.343-414.

Pegram, G. G. S., 1980 : On reservoir reliability.  
Jnl. of Hydrology, 47, pp. 269-296.

Penman, H. L., 1948 : Natural evaporation from open water,  
bare soil and grass. Proc. Roy. Soc. London,  
Series A, 193, p.120.

Penman, H. L., 1949 : The dependence of transpiration on weather and soil conditions. Jnl. Soil. Sci., 1, p.74.

Perry, A. H., 1976 : The long drought of 1975-76. Weather, 31, pp. 328-334.

Perthshire Advertiser : 9.9.72 to 21.3.73.

Riggs, H. C., 1968 : Frequency curves. Techniques of Water Resources Investigations of the United States Geological Survey, Book 4, Chapter A2, 15pp.

Rodier, J. A., 1975 : Evaluation de l'ecoulement annuel dans le Sahel Tropical Africain. Travaux et Documents de L'O.R.S.T.O.M., No. 46, Office de la Recherche Scientifique et Technique Outre-Mer, Paris.

Roy, M. G., et al, 1978 : Some agricultural effects of the drought of 1975-76 in the U.K. Weather, 33, pp.64-74.

Royal Commission on Water Supply, The, 1867 : In Report of the Duke of Richmond's Commission, 1869, p.27.

Royal Society, The, 1978 : Scientific Aspects of  
the 1975-76 Drought in England and  
Wales, The Royal Society, London, 133pp.

Russel, 1896 : reported by Foley, 1957; see this  
bibliography.

Russel, C. S., Arey, D. G., and Kates, R. W., 1970 :  
Drought and Water Supply - Implications of  
the Massachusetts Experience for Municipal  
Planning, The John Hopkins Press, Baltimore,  
U.S.A., 232pp.

St. Andrews Citizen : 26.5.73 to 13.10.73.

Samuels, A., 1977 : Water Law. Local Govt. Review,  
141, No. 3, pp.31-33.

Sanders, P. F., 1980 : personal communication.

Scottish Development Department, 1972 : Towards  
Cleaner Water - Report of a Rivers Pollution  
Survey of Scotland, pp. 37. H.M.S.O., Edinburgh.

Scottish Development Department, 1973a : A Measure  
of plenty; Water Resources in Scotland -  
A General Survey, pp. 99. H.M.S.O., Edinburgh.



Scottish Development Department, 1973b : Water Supply  
in Scotland, March 1973. Unpublished Report.

Scottish Development Department, 1980 : personal communication.

Search, J. K., 1959 : Flow duration curves.  
U.S. Geol. Survey, Water Supply Paper 1542-A.

Snedecor, G. W., and Cochran, W. G., 1973 : Statistical Methods. Iowa State University Press.

Solway River Purification Board, 1971 to 76 : S.R.P.B. Annual Reports, S.R.P.B., Dumfries.

Spray Irrigation (Scotland) Act, 1964 : H.M.S.O., Edinburgh.

Subrahmanyam, V. P., 1967 : Incidence and spread of continental drought. W.M.O./I.H.D. Report No. 2, 51pp.

Tabony, R. C., 1977a : Drought classification and a study of droughts at Kew. Met. Mag., 106, pp.1-10.

Tabony, R. C., 1977b : The variability of long duration rainfall over Great Britain. Met. Office Scientific Paper 37 (Met.0.901), H.M.S.O., 40pp.

- Takeuchi, K., 1973 : Regional water exchange systems as an alternative for alleviating drought problems. In Floods and Droughts, Proc. 2nd Int. Symp. in Hydrology, Fort Collins, Colorado, U.S.A., pp.561-582.
- Tannehill, I. R., 1947 : Drought - Its Causes and Effects. Oxford University Press.
- Tapp, J. S., 1976 : Wastewater storage - simulation of instream effects. Am. Soc. Civ. Engrs., Proc. Jnl. of the Environmental Engineering Division, 102, No.EE6, pp.1151-1159.
- Tase, N., 1976 : Area - deficit - intensity characteristics of droughts. Hydrology Paper 87, Colorado State University, Fort Collins, Colorado, 40pp.
- Tay River Purification Board, 1971 to 76 : T.R.P.B. Annual Reports, T.R.P.B., Perth.
- Thom, A. S., and Ledger, D. C., 1976 : Rainfall, run-off and climatic change. Proc. Instn. Civ. Engrs., Part 2, 61, pp.633-652.
- Thomas, D. M., and Benson, M. A., 1970 : Generalisation of streamflow characteristics from drainage basin characteristics. U. S. Geol. Survey, Water Supply Paper No. 1975.

- Thornthwaite, C. W., 1947 : Climate and moisture conservation. Annals Assoc. Amer. Geogrs., 37 (2), pp. 87-100.
- Tickell, C., 1977 : Climatic Change and World Affairs. Harvard Studies in International Affairs No. 37, Pergamon Press, Oxford.
- Tweed River Purification Board, 1970-79 : T.R.P.B. Annual Reports, T.R.P.B., Galashiels.
- Villela, S. M., 1973 : Simulation model for the decision between dilution or sewage treatment during drought. In Floods and Droughts, Proc. 2nd Int. Symp. in Hydrology, Fort Collins, Colorado, U.S.A., pp. 523-533.
- Walds-Lewis, R. P., and McIntosh, D. H., 1952 : Some effects of the coherence of meteorological time series. Met. Mag., 81, pp.242-244.
- Ward, R. C., 1980 : In, Atlas of Drought in Britain 1975-76. See entry under Doornkamp et al.
- Water (Scotland) Act, 1946 : H.M.S.O., Edinburgh.
- Water (Scotland) Act, 1958 : H.M.S.O., Edinburgh.



- Wiebull, W., 1939 : A statistical theory on the strength of material. IngvetenskAkad. Handl., 151, p.15.
- Woodward, G., 1907 : Stanford's Geological Atlas of Great Britain and Ireland, 2nd Edition, Edward Stanford, London, 187pp.
- World Meteorological Organisation, 1975a : Drought and Agriculture. Technical Note No. 138, W.M.O. publn. No. 392, W.M.O., Geneva, Switzerland, 127pp.
- World Meteorological Organisation, 1975b : Drought. Special Environmental Report No. 5, W.M.O. publn. No. 403, W.M.O., Geneva, Switzerland, 113pp.
- Wright, P. B., 1975 : The weather machine - skating on thin ice. Weather, 30, pp.123-125.
- Wuhrmann, K., and Woker, H., 1955 : Influence of temperature and oxygen tension on the toxicity of poisons to fish. Ver. Int. Ver. Limnol, 12, pp.795-801.
- Yevjevich, V., 1967 : An objective approach to definitions and investigations of continental (cont'd. overleaf)

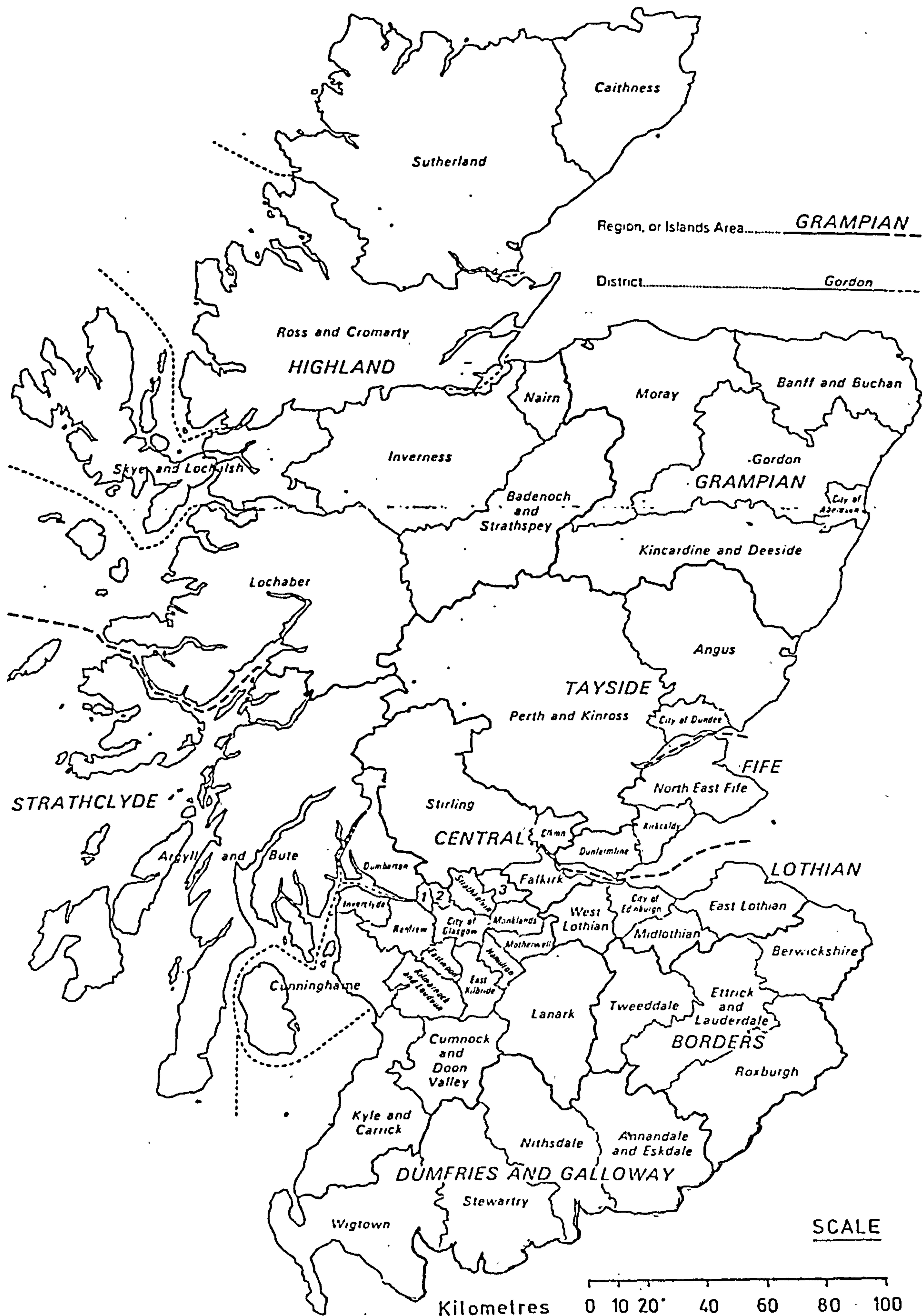
hydrologic droughts. Hydrology Paper No. 23,  
Colorado State Univ. Press, Fort Collins,  
Colorado, U.S.A., pp. 18.

Young, J. A., 1976 : Control of water supply  
demand. General Report No. 2,  
I.W.S.A. Conference, Sept. 1976, Amsterdam,  
Holland.

Young, J. A., 1977 : User economy and publicity.  
In The Drought of 1975-76. Proceedings of  
a seminar by the Instn. of Water Engrs.  
and Scientists, and the Instn. of Civ. Engrs.,  
29th March, 1977, London.

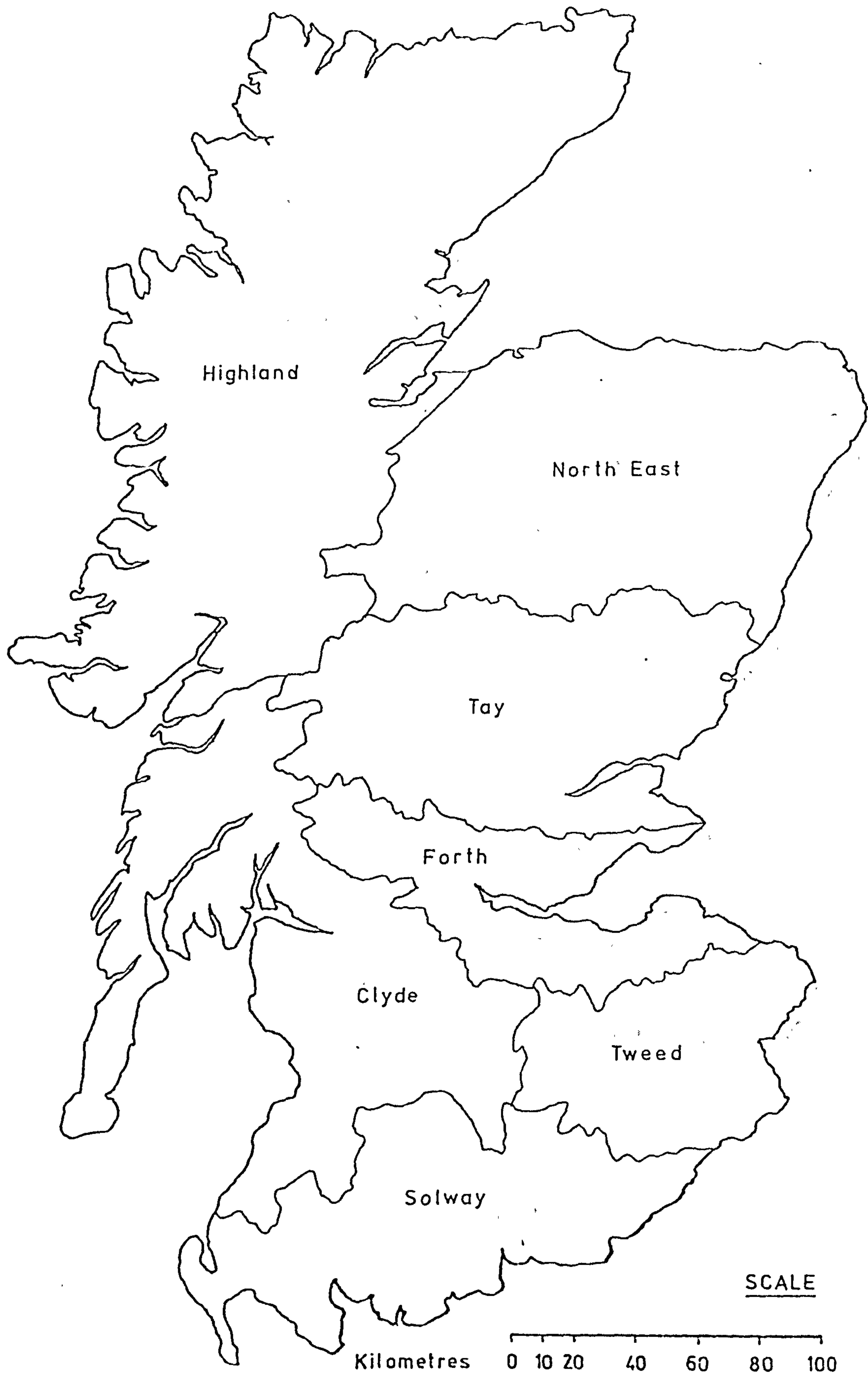
## APPENDIX 1

### 1.1 Administrative Areas in Scotland Since 1975

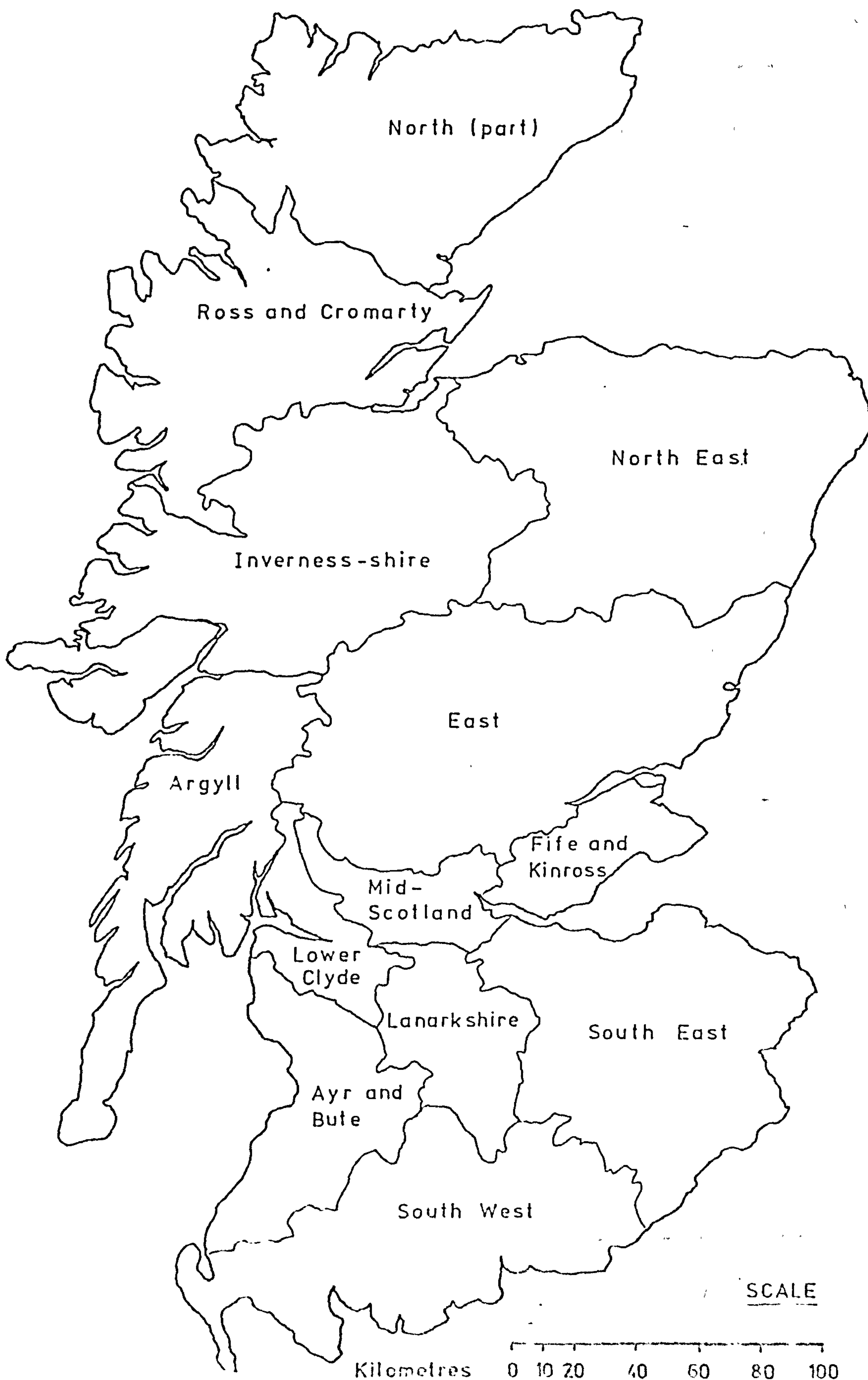




## 1.2 River Purification Board Areas in Scotland



### 1.3 Water Board Areas in Scotland From 1968 to 1974



## APPENDIX 2

### 2.1 Sources, Locations and Types of Hydrometeorological Data Presented in the Thesis

Source		Data Presented		
Station	Location (Fig.2.4)	Precipitation		Water Balance (Fig.2.8)
		Annual (Fig.2.4)	Monthly (Fig.2.5)	
A	Wick	✓	✓	
B	Inverness	✓	✓	
C	Fyne C.	✓	✓	
D	Braemar	✓	✓	
E	Invery H.	✓	✓	
F	Leuchars	✓	✓	✓
G	Br. of Allan	✓	✓	
H	Blackford H	✓	✓	
I	Prestwick	✓	✓	✓
J	Eskdalemuir	✓	✓	
K	Lairg	✓		
L	Poolewe	✓		
M	Kinloss	✓		✓
N	Dyce	✓		✓
O	Dunstaffriage	✓		
P	Montrose	✓		
Q	Haddington	✓		
R	Carnwath	✓		
S	Lochton	✓		
T	Turnhouse			✓
U	Dumfries	✓		



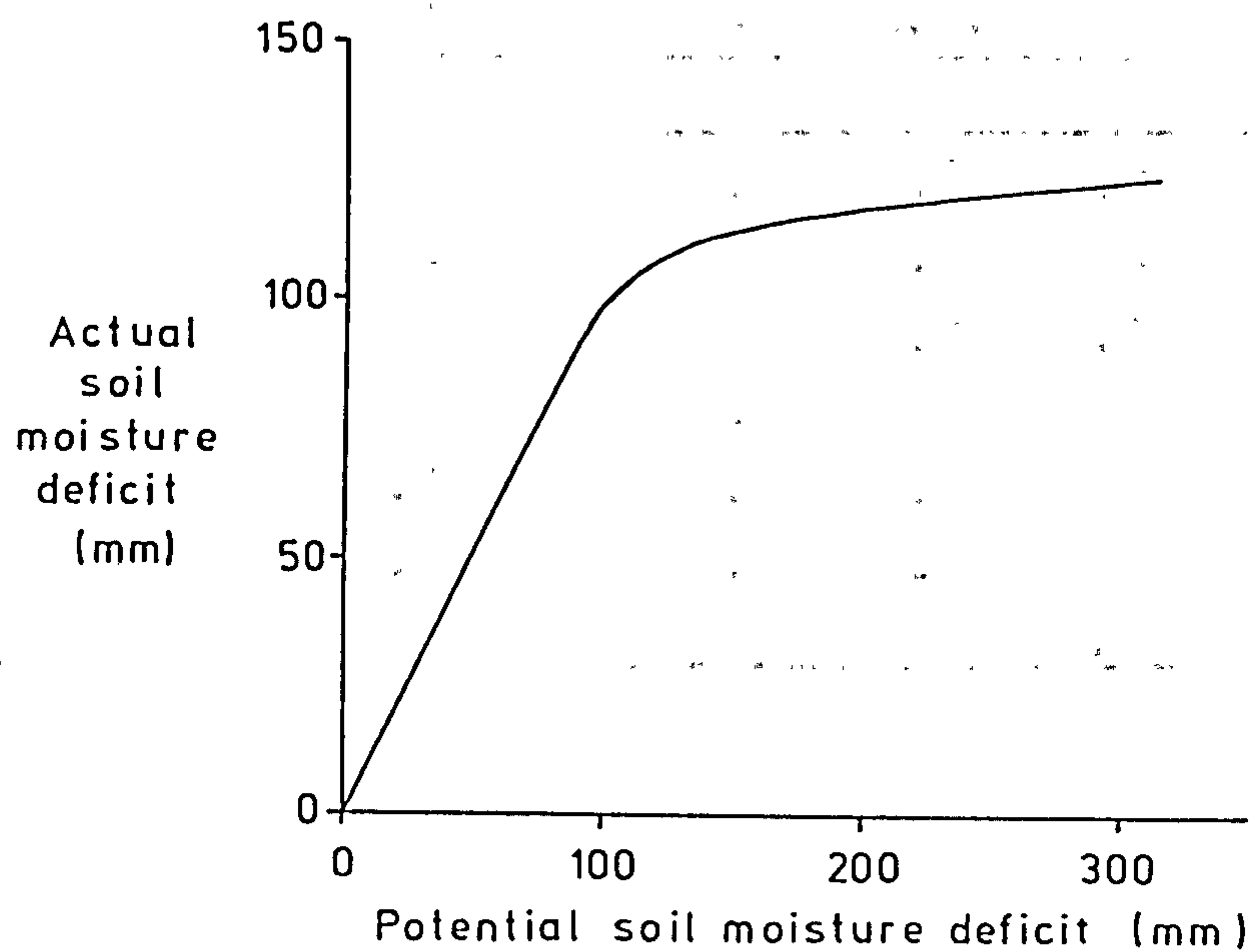
2.2 Details of Gauged Catchments Shown in Fig. 2.10  
and Table 2.2

Ref. No.	Gauging Station	Authority (R.P.B.)	Water-Course	Catchment area (km <sup>2</sup> )
1	Balnann	North East	Dulnain	272
2	Avochie	North East	Deveron	442
3	Woodend	North East	Dee	1370
4	Cookston	Tay	Dean	177
5	Glenochil	Forth	Devon	181
6	Craigiehall	Forth	Almond	369
7	E. Linton	Forth	Tyne	307
8	Fairholm	Clyde	Avon	265
9	Lyne Ford	Tweed	Tweed	373
10	Hawick	Tweed	Teviot	323
11	Halkirk	Highland	Thurso	413
12	Ardlethan	North East	Ythan	448
13	Kemback	Tay	Eden	307
14	Friars Carse	Solway	Nith	799

### APPENDIX 3

#### The Relationship Between Potential and Actual Maximum Soil Moisture Deficit for a Root Constant of 75mm.

Source : Penman (1949)



# APPENDIX 4

Tabulated Flow Duration Data for Catchments Shown in  
Fig. 2.14 : for the Period 1961-78 and the Individual Years  
1971-76

Gauging Station : Balnaan  
Station No. : 1  
Watercourse : Dulnain  
Catchment Area : 272 km<sup>2</sup>

Period	Flow (l s <sup>-1</sup> km <sup>-2</sup> ) at given percentiles						
	90	50	20	10	5	2	1
1961-78	35.0	12.4	6.9	5.1	4.2	3.7	3.3
1971	26.2	10.4	5.8	5.0	4.7	4.4	4.3
1972	26.2	9.5	4.3	3.8	3.5	3.2	3.1
1973	44.2	11.0	6.2	5.0	4.2	3.3	2.7
1974	46.3	10.2	4.7	4.0	3.8	3.7	3.6
1975	47.8	12.9	6.4	4.8	4.1	3.9	3.9
1976	30.6	10.2	4.9	3.5	2.6	2.4	2.4

Gauging Station : Avochie  
Station No. : 2  
Watercourse : Deveron  
Catchment Area : 442 km<sup>2</sup>

Period	Flow (l s <sup>-1</sup> km <sup>-2</sup> ) at given percentiles						
	90	50	20	10	5	2	1
1961-78	36.5	13.2	7.4	5.8	5.1	4.5	4.1
1971	22.0	9.0	5.4	5.0	4.9	4.7	4.6
1972	21.3	8.4	4.8	4.5	4.3	4.3	4.2
1973	28.9	7.6	5.2	4.8	4.6	4.5	4.5
1974	37.2	13.3	6.3	5.4	5.0	4.9	4.8
1975	22.6	10.7	6.4	6.0	5.7	5.4	5.2
1976	28.3	10.7	4.7	3.8	3.5	3.2	3.1



Gauging Station : Cookston  
Station No. : 4  
Watercourse : Dean  
Catchment Area : 177 km<sup>2</sup>

Period	Flow (l s <sup>-1</sup> km <sup>-2</sup> ) at given percentiles						
	90	50	20	10	5	2	1
1961-78	27.5	8.6	4.7	3.9	3.5	3.1	2.9
1971	16.6	7.5	5.1	4.0	3.5	3.2	3.1
1972	36.9	8.2	4.2	3.8	3.6	3.6	3.5
1973	10.6	4.1	3.2	3.0	2.7	2.5	2.2
1974	33.8	8.2	4.4	4.2	4.1	3.9	3.8
1975	19.8	5.0	3.8	3.3	3.0	2.9	2.8
1976	33.8	9.6	4.2	3.0	2.4	2.3	2.3

Gauging Station : Glenochil  
Station No. : 5  
Watercourse : Devon  
Catchment Area : 181 km<sup>2</sup>

Period	Flow (l s <sup>-1</sup> km <sup>-2</sup> ) at given percentiles						
	90	50	20	10	5	2	1
1961-78	46.0	14.6	8.5	6.5	5.4	4.6	4.1
1971	29.0	11.3	6.1	5.2	4.8	4.4	4.1
1972	30.3	11.6	6.0	4.7	4.2	3.6	3.6
1973	20.2	9.1	6.6	5.8	5.4	4.9	4.5
1974	52.5	11.0	6.2	5.2	4.7	4.3	3.9
1975	40.0	8.5	5.3	4.5	4.1	3.8	3.6
1976	53.2	14.0	7.0	5.3	4.3	3.7	3.5

Gauging Station : Craigiehall  
Station No. : 6  
Watercourse : Almond  
Catchment Area : 369 km<sup>2</sup>

Period	Flow (l s <sup>-1</sup> km <sup>-2</sup> ) for given percentiles						
	90	50	20	10	5	2	1
1961-78	28.0	7.4	3.7	2.9	2.3	2.0	1.7
1971	27.2	6.6	3.9	2.9	2.2	1.7	1.5
1972	23.0	5.8	2.6	2.0	1.8	1.5	1.5
1973	16.3	4.8	2.9	2.2	2.0	1.9	1.8
1974	35.2	6.0	2.9	2.2	1.8	1.3	1.2
1975	25.7	5.1	3.0	2.4	2.2	1.9	1.6
1976	28.5	6.6	3.3	2.5	2.2	2.0	1.9

Gauging Station : East Linton  
Station No. : 7  
Watercourse : Tyne  
Catchment Area : 307 km<sup>2</sup>

Period	Flow (l s <sup>-1</sup> km <sup>-2</sup> ) for given percentiles						
	90	50	20	10	5	2	1
1961-78	26.6	5.0	2.6	2.0	1.8	1.6	1.5
1971	11.1	3.4	2.1	1.8	1.7	1.6	1.5
1972	16.2	2.6	1.6	1.5	1.5	1.4	1.4
1973	3.4	1.9	1.6	1.5	1.4	1.3	1.2
1974	12.8	3.4	2.5	2.0	1.7	1.5	1.4
1975	11.9	4.2	2.4	2.0	1.9	1.8	1.8
1976	14.7	3.5	2.0	1.5	1.4	1.3	1.3

Gauging Station : Fairholm  
Station No. : 8  
Watercourse : Avon  
Catchment Area : 265 km<sup>2</sup>

Period	Flow (l s <sup>-1</sup> km <sup>-2</sup> ) at given percentiles						
	90	50	20	10	5	2	1
1961-78	68.0	11.0	3.7	2.3	1.7	1.2	1.0
1971	54.0	8.8	2.8	2.0	1.2	0.9	0.8
1972	28.3	7.9	2.2	1.4	1.2	1.1	1.0
1973	59.8	7.0	1.9	1.5	1.3	1.2	1.1
1974	72.5	9.1	2.4	1.8	1.3	1.0	0.8
1975	61.1	7.2	2.1	1.3	1.1	1.0	0.9
1976	39.2	9.4	2.3	1.4	0.8	0.6	0.6

Gauging Station : Lyne Ford  
Station No. : 9  
Watercourse : Tweed  
Catchment Area : 373 km<sup>2</sup>

Period	Flow (l s <sup>-1</sup> km <sup>-2</sup> ) at given percentiles						
	90	50	20	10	5	2	1
1961-78	40.2	14.1	8.2	6.3	5.4	4.7	4.2
1971	32.5	13.3	7.3	6.1	5.6	5.3	5.1
1972	38.0	14.1	5.5	4.3	3.7	3.3	3.3
1973	22.2	10.0	6.6	5.4	5.0	4.8	4.7
1974	57.0	12.0	5.7	5.3	5.2	4.9	4.8
1975	38.6	9.6	6.2	4.9	4.5	4.4	4.4
1976	31.2	16.7	7.6	5.0	4.2	3.8	3.7



Gauging Station : Hawick

Station No : 10

Watercourse : Teviot

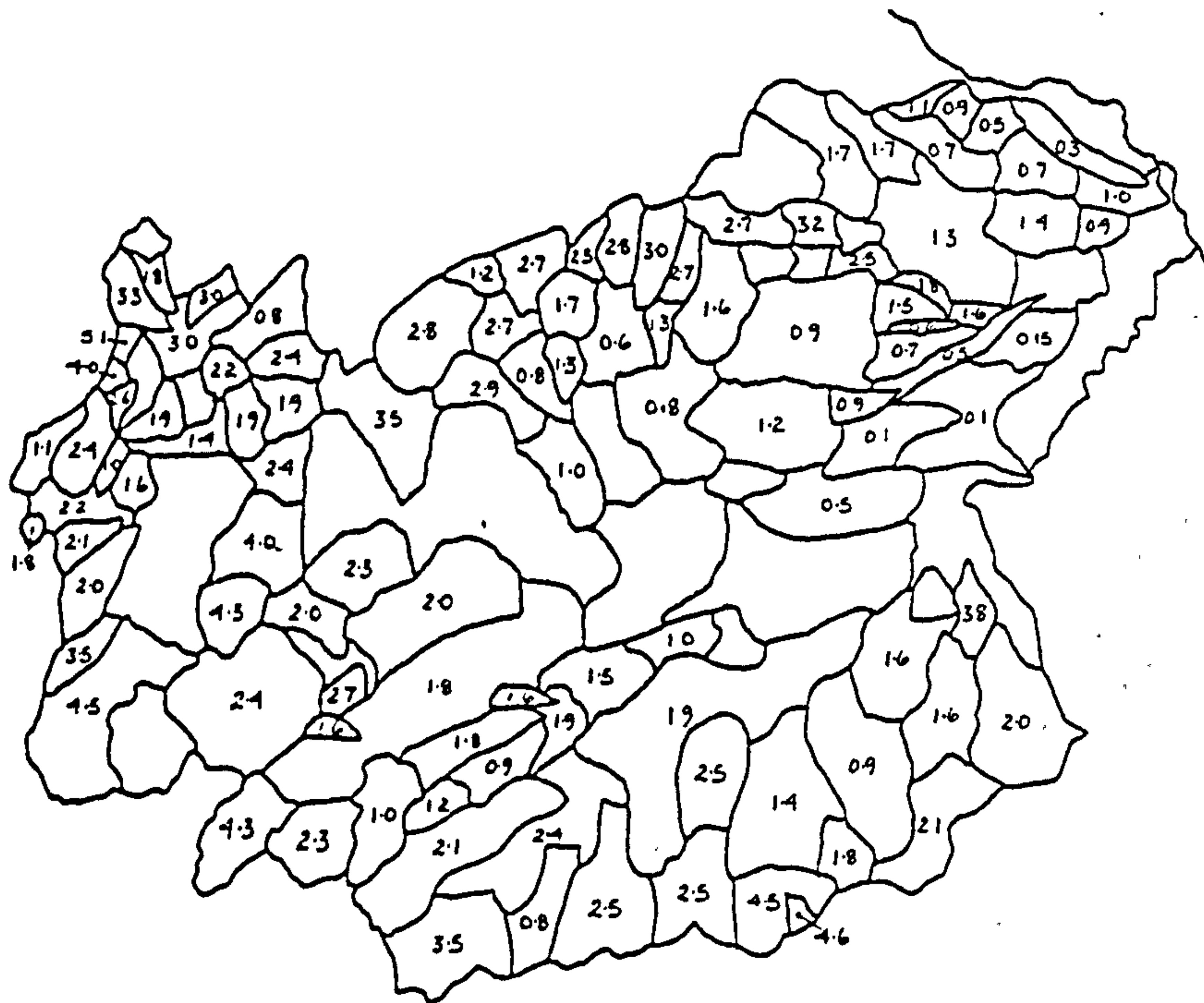
Catchment Area : 323 km<sup>2</sup>

Period	Flow (l s <sup>-1</sup> km <sup>-2</sup> ) at given percentiles						
	90	50	20	10	5	2	1
1961-78	51.0	15.2	7.0	4.5	3.2	2.6	2.3
1971	44.5	12.9	4.9	4.1	3.5	2.6	2.4
1972	48.0	14.0	3.8	2.6	2.2	1.9	1.9
1973	28.2	8.6	4.8	3.8	3.2	2.8	2.7
1974	75.0	13.0	4.4	3.2	2.6	2.2	2.1
1975	49.3	11.2	6.0	3.6	2.9	2.5	2.4
1976	35.2	13.6	4.2	2.9	2.4	2.1	2.0

## APPENDIX 5

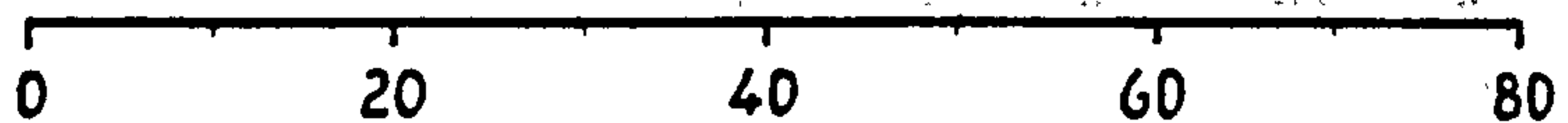
### 5.1 1 Percentile Run-Off Yields for Individual Nested Catchments in Eastern Scotland, by River Purification Board Areas: (in $\text{l s}^{-1} \text{km}^{-2}$ ).

#### (1) Tweed

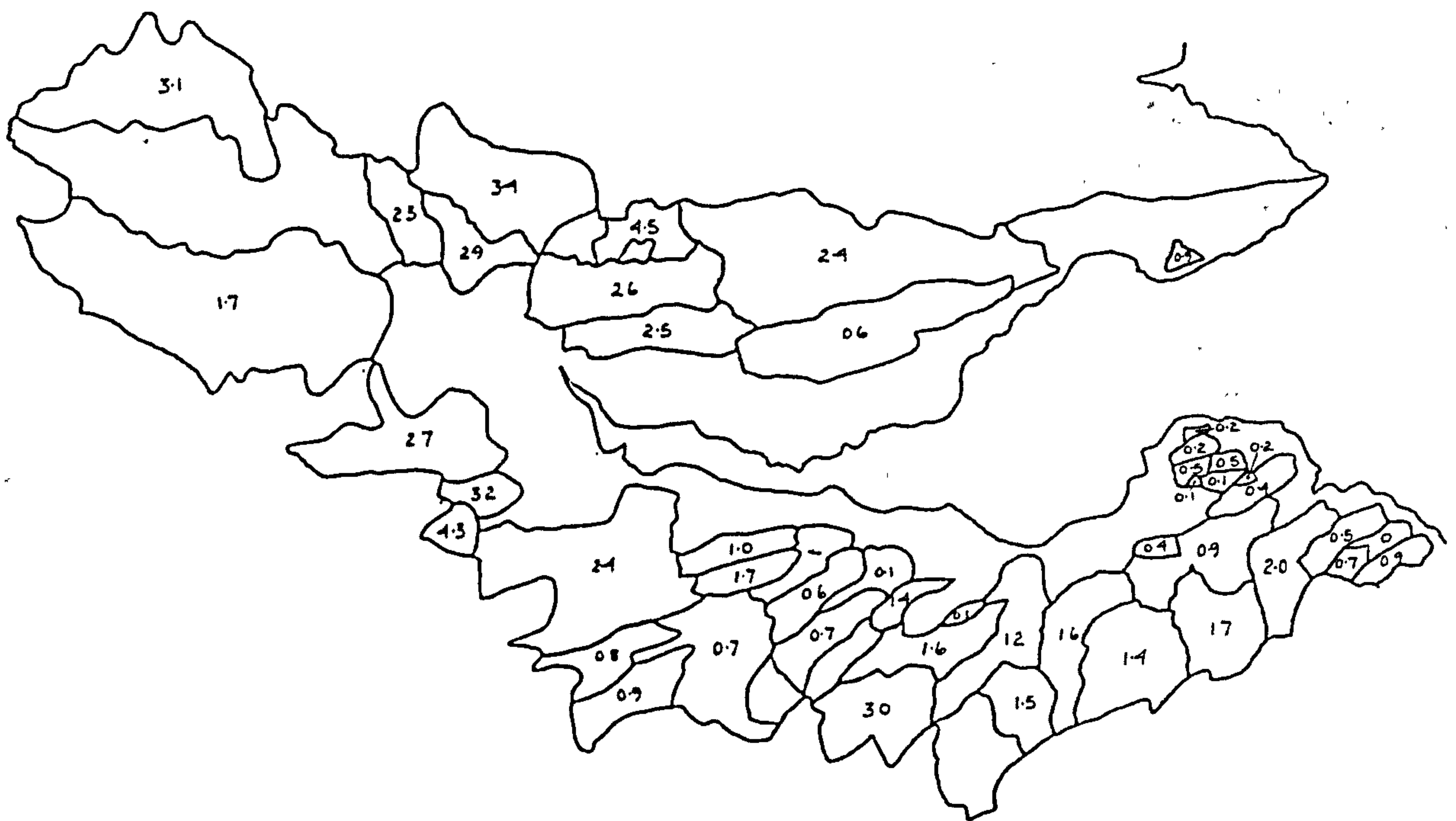


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Kilometres

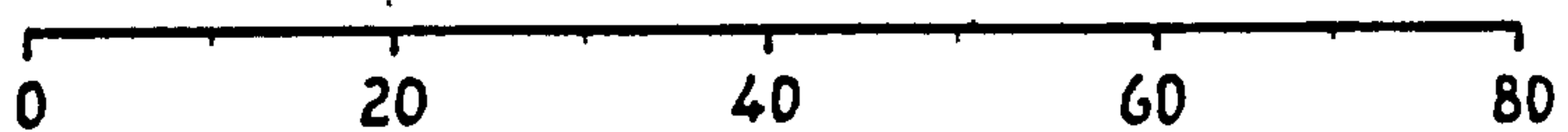


(2) Forth



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# Kilometres



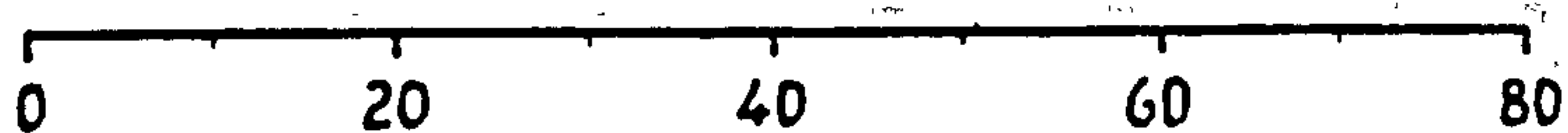


(3) Tax

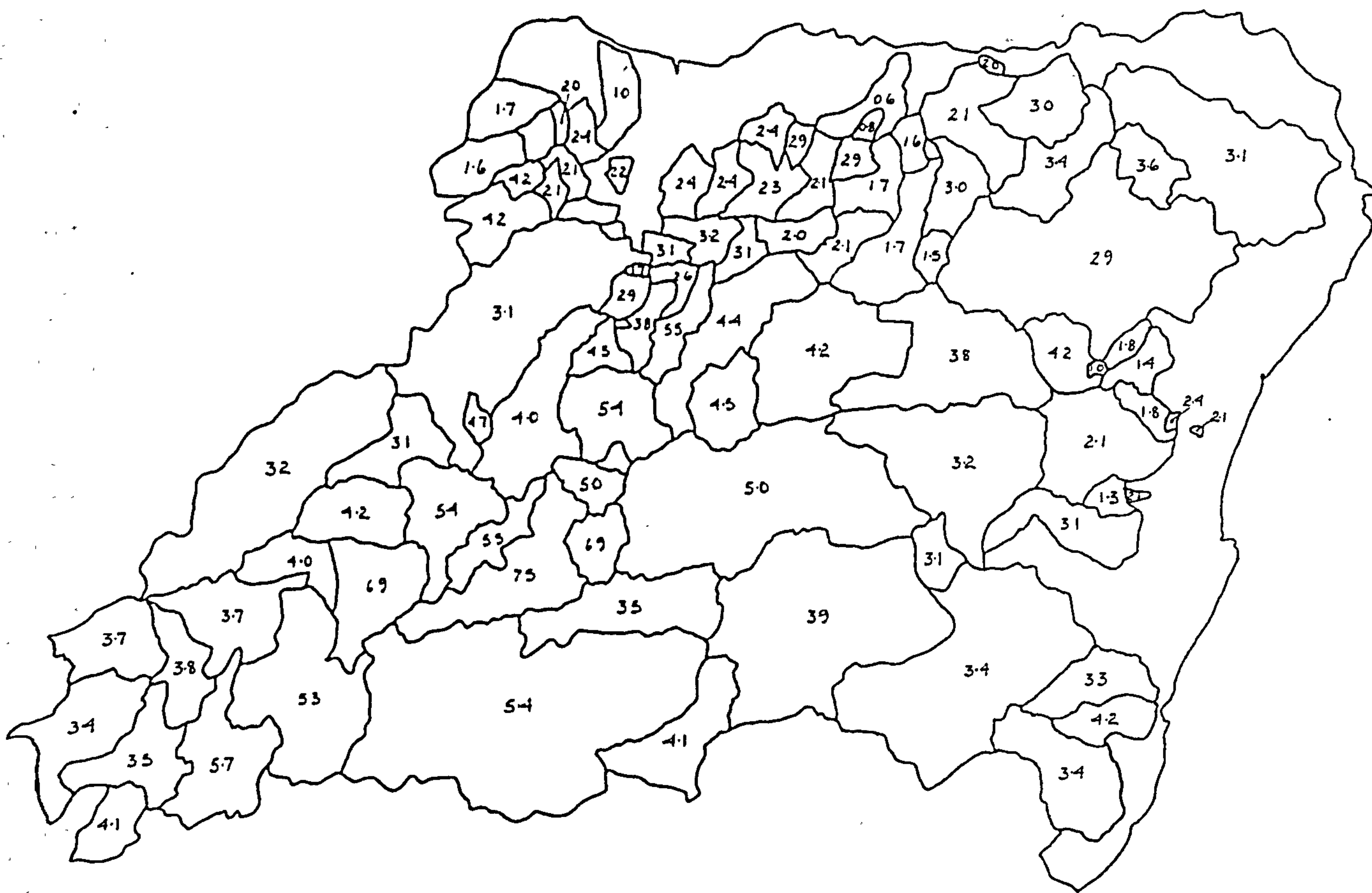


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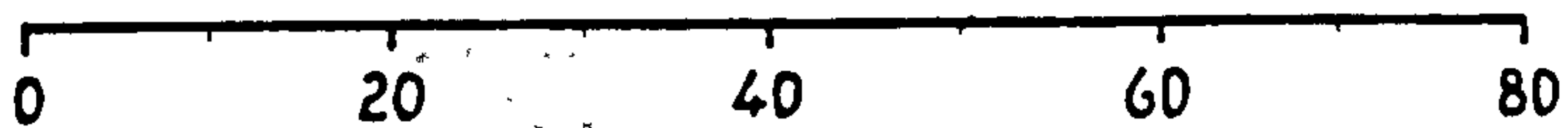


(4) North East

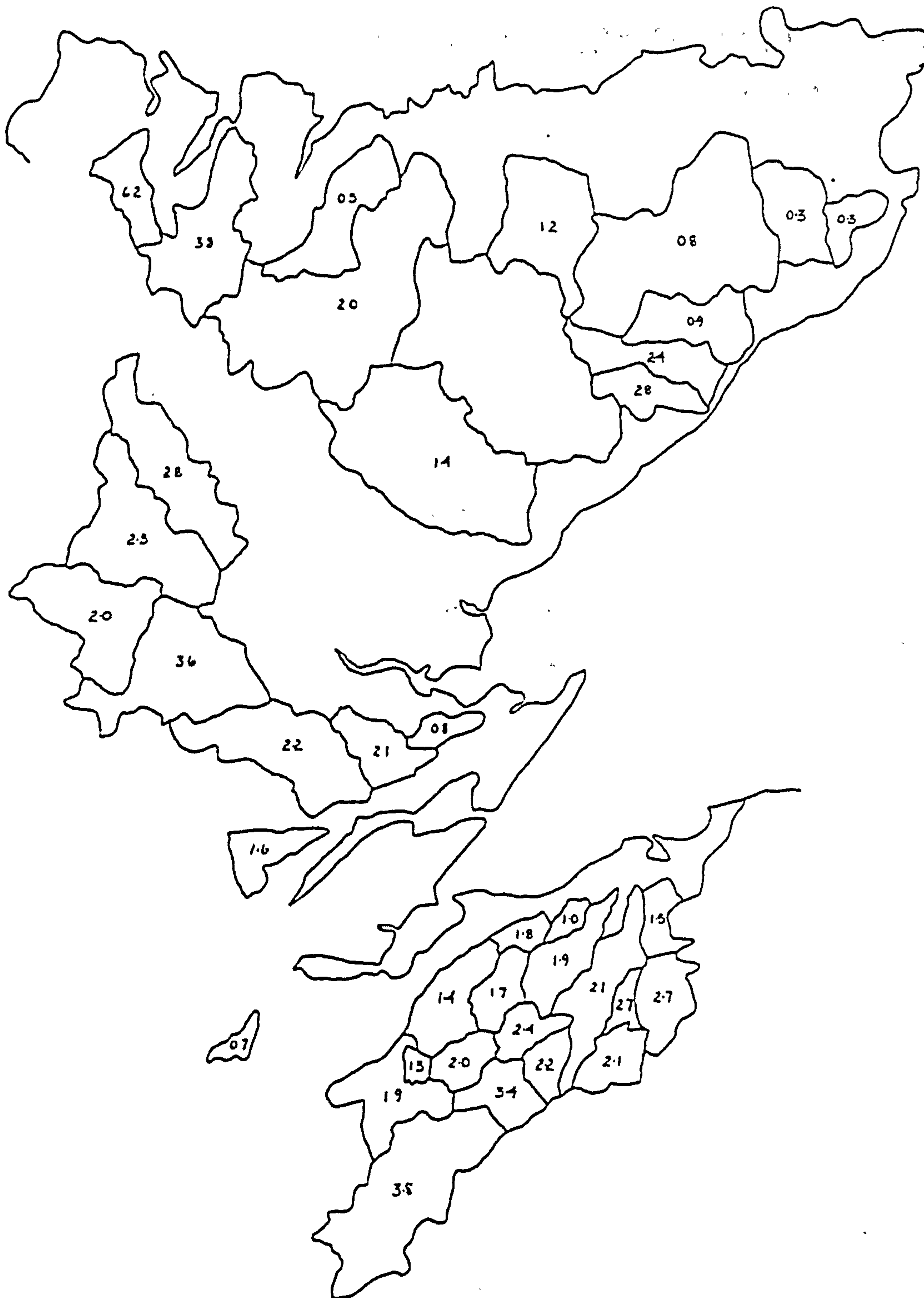


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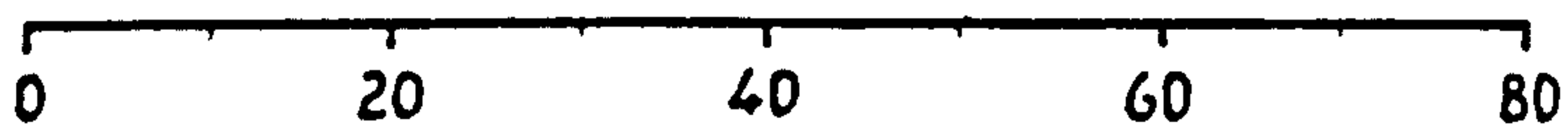


(5) Highland



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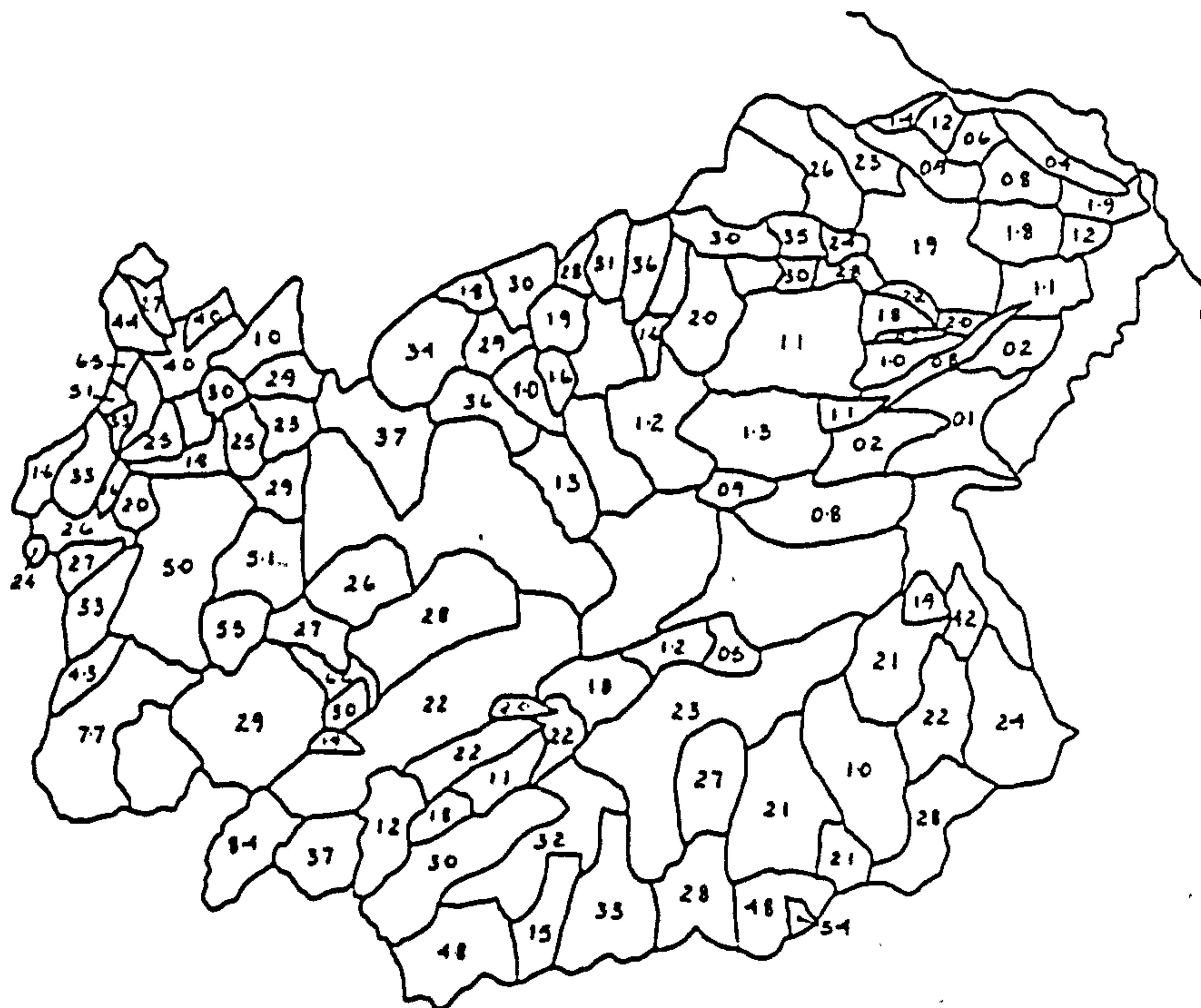
Kilometres





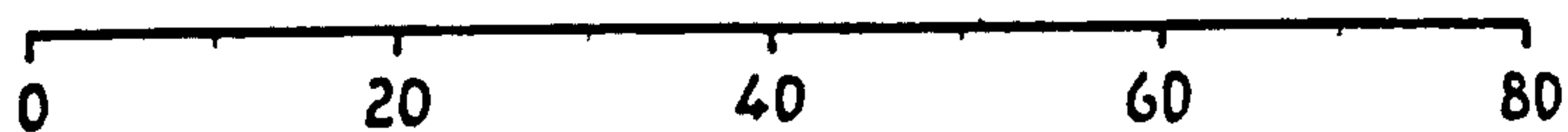
5.2 5 Percentile Run-Off Yields for Individual Nested Catchments in Eastern Scotland, by River Purification Board Areas: (in  $\text{L s}^{-1} \text{km}^{-2}$ )

(1) Tweed

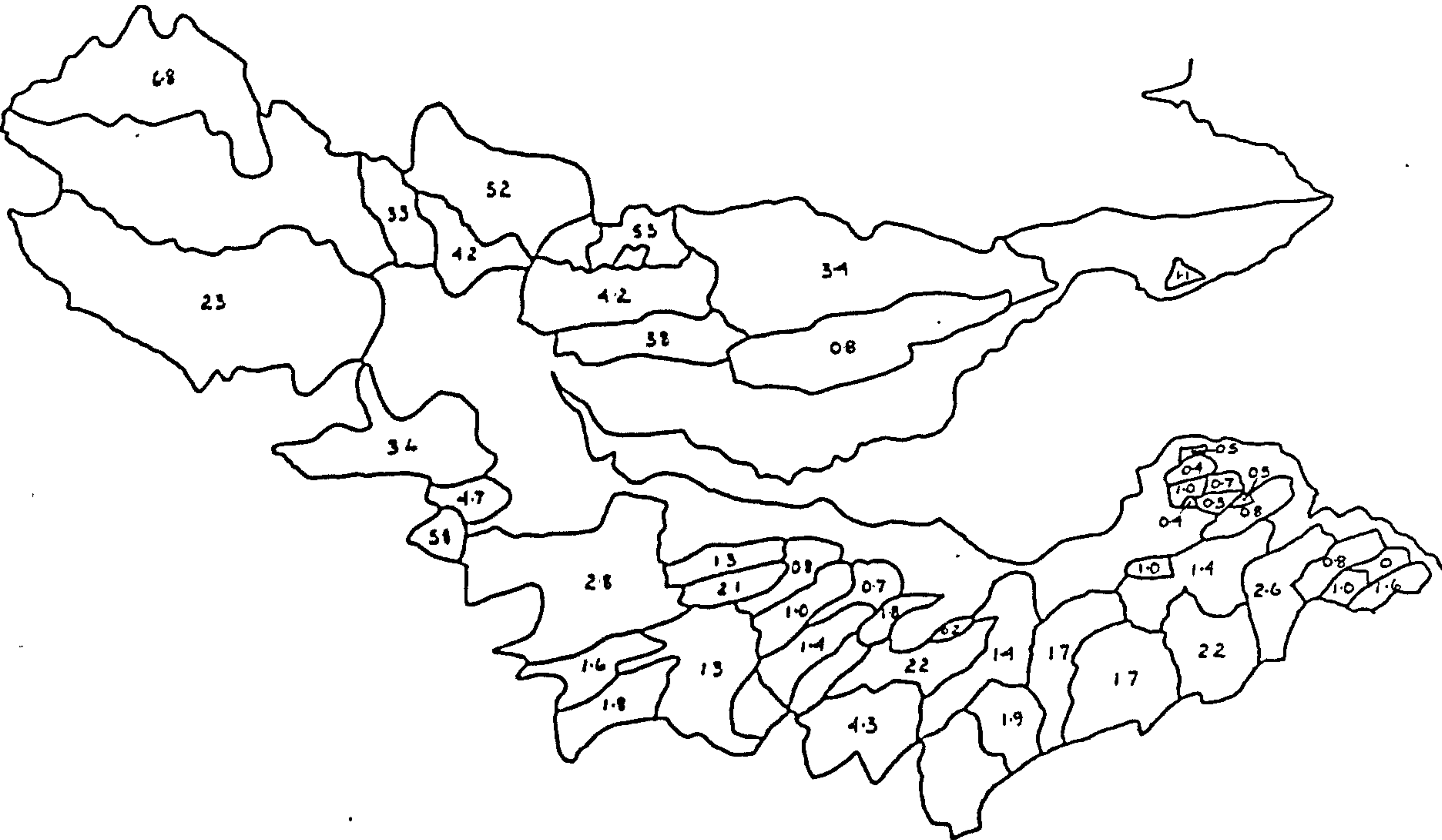


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Kilometres

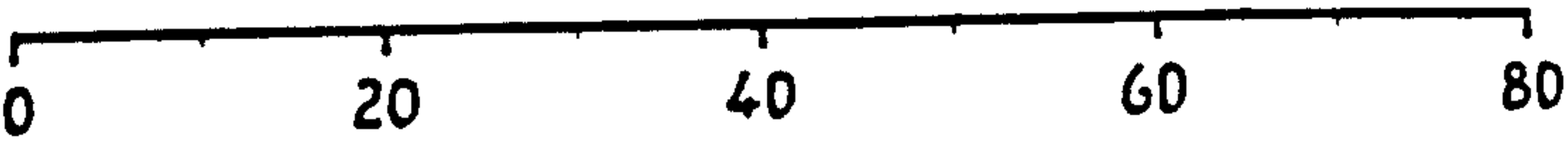


(2) Forth

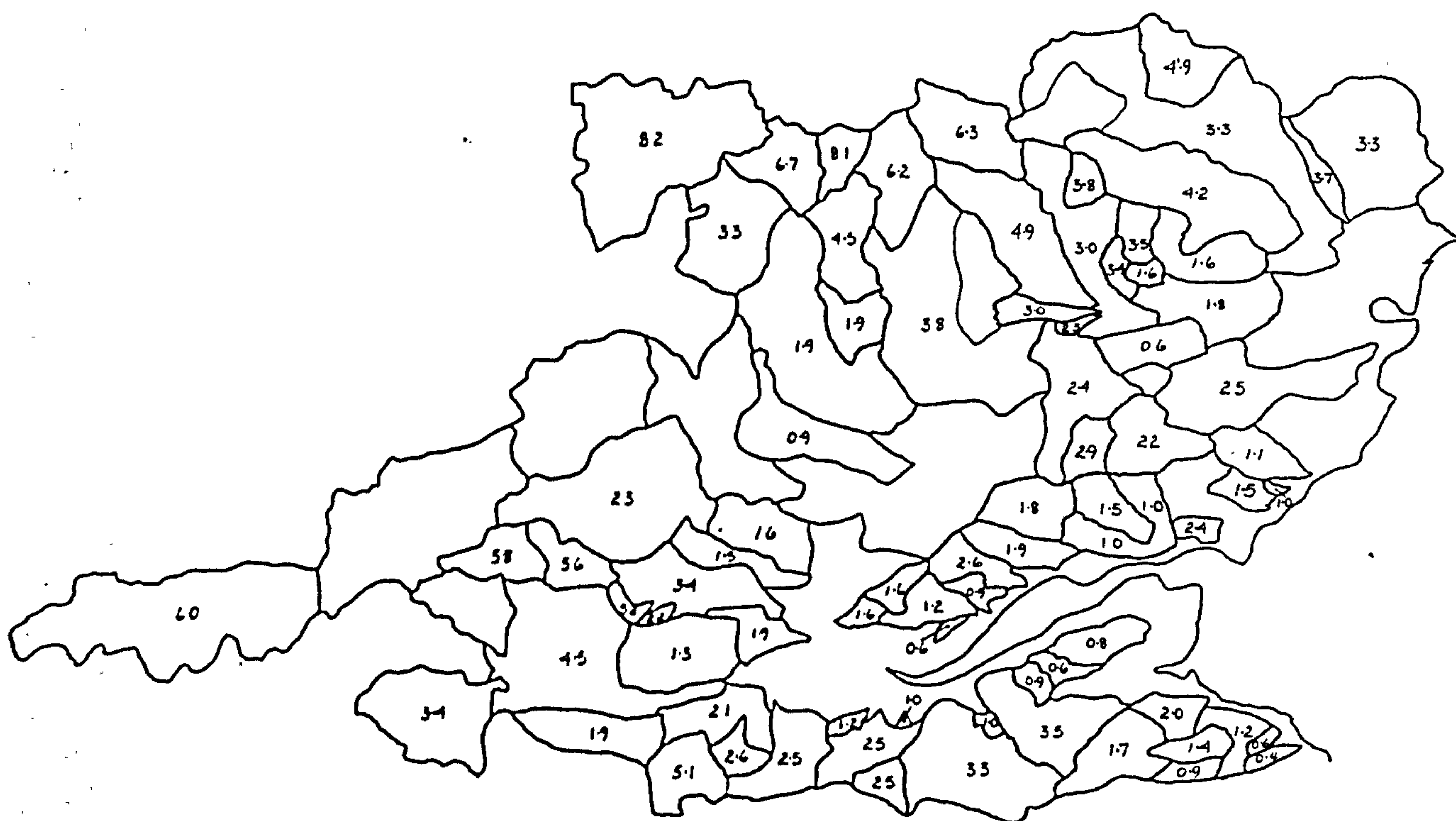


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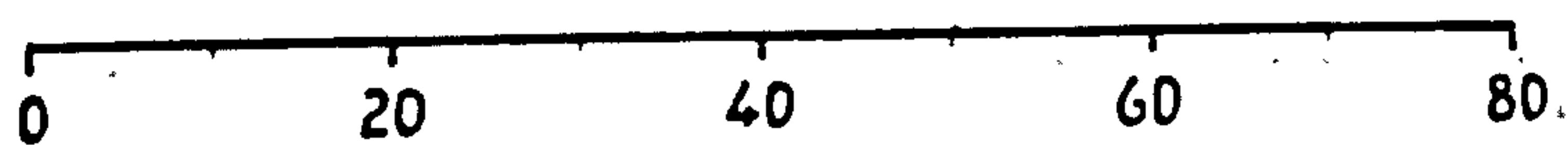


(3) Tax



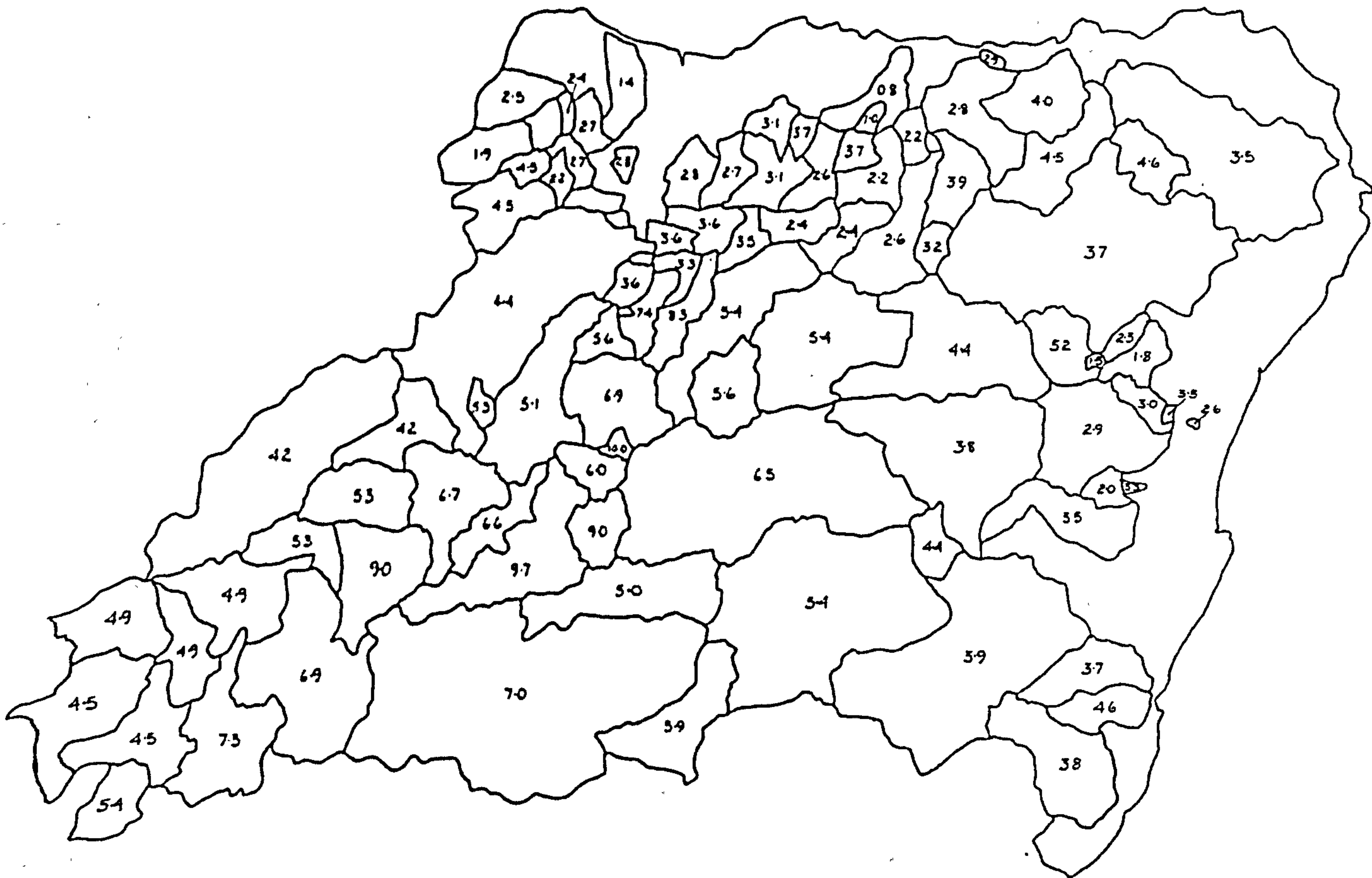
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## Kilometres



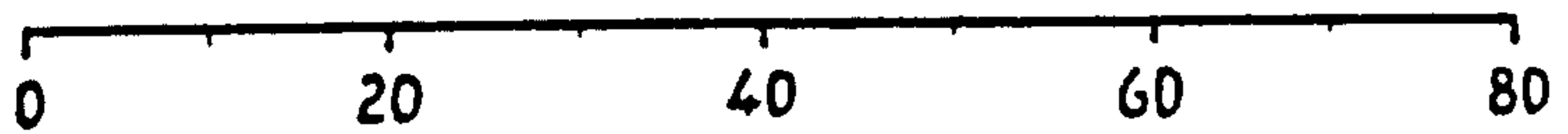


(4) North East

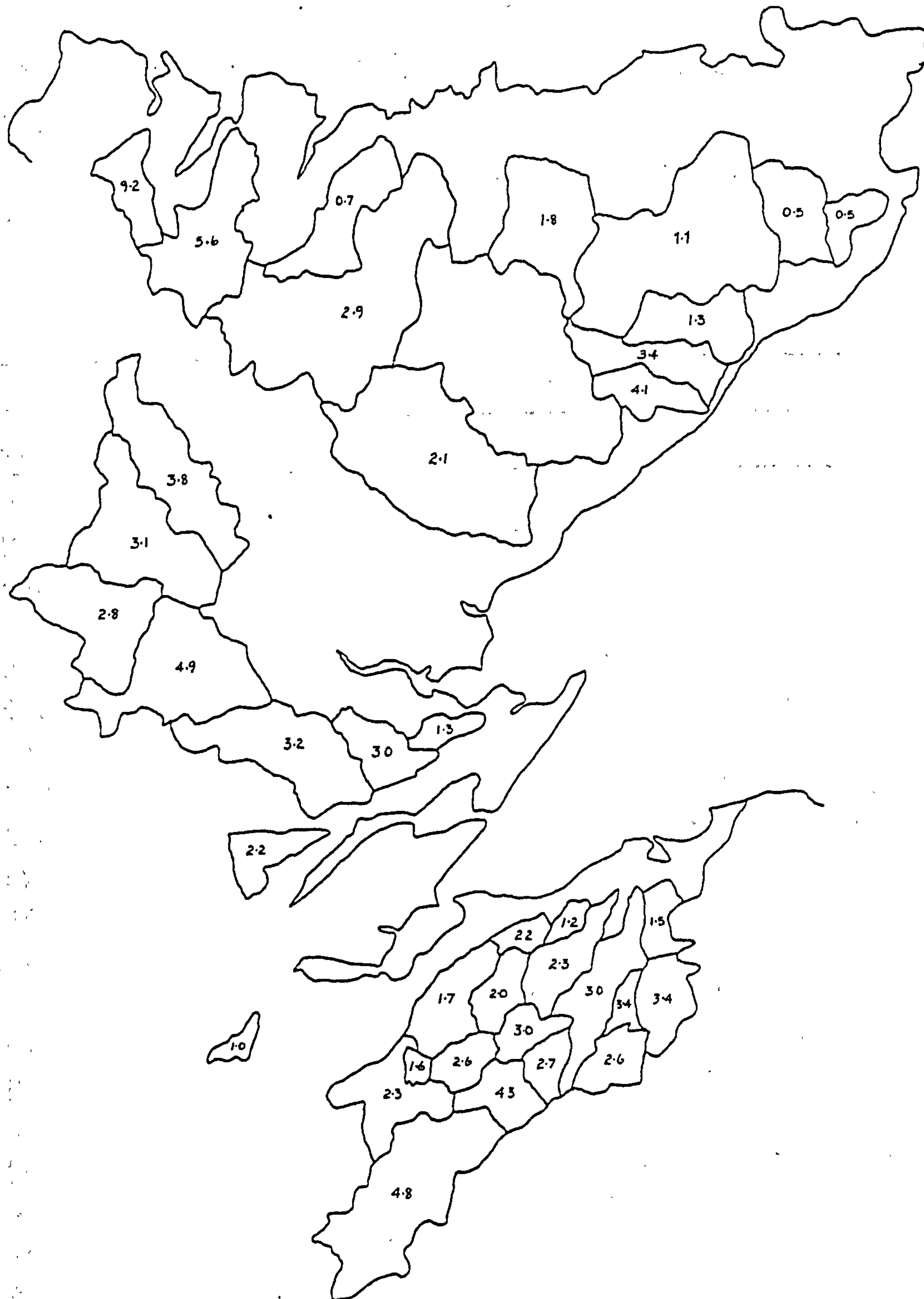


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# Kilometres

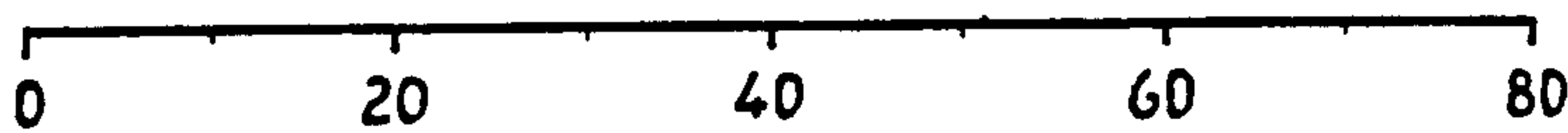


(5) Highland



SCALE

Kilometres



# APPENDIX 6

## Annual Precipitation (mm) at Blackford Hill, Edinburgh Since 1780

Sources : Mossman, R. C., 1896 : Trans. Roy. Soc. Edin., 38, pp.681-775.  
: Meteorological Office

Decade (1st Year)	Year of Decade									
	0	1	2	3	4	5	6	7	8	9
1780	576					778	595	812	494	742
1790	699	606	940	526	730	930	448	690	574	673
1800	548	518	541	402	624	411	558	566	738	759
1810	684	829	688	512	566	554	641	749	542	687
1820	576	602	664	769	630	562	388	828	641	761
1830	844	623	590	530	534	641	839	680	788	596
1840	648	666	428	604	532	676	801	578	777	564
1850	519	579	800	651	531	517	723	633	618	660
1860	850	727	862	651	714	601	692	788	726	565
1870	562	682	990	716	654	618	905	909	632	724
1880	631	717	768	567	626	446	662	503	631	567
1890	680	615	569	532	718	679	616	579	564	650
1900	796	577	418	814	611	494	794	767	540	751
1910	699	538	684	520	578	685	991	536	614	646
1920	699	628	540	615	726	808	785	874	840	611
1930	805	810	727	556	687	702	640	736	723	565
1940	706	638	566	582	749	716	624	658	924	711
1950	733	787	619	600	892	458	714	650	748	457
1960	618	643	656	768	503	826	731	637	809	559
1970	599	565	472	458	626	604	633	782		



## APPENDIX 7

### 7.1 Serial Correlation Coefficients up to the 6<sup>th</sup> Degree for Annual Water-Year Rainfall and Run-Off for the Gladhouse Reservoir Catchment (1885-1976)

Degree (i)	Serial correlation coefficient ( $r_i$ )	
	Run-Off	Rainfall
1	-0.053	0.041
2	0.022	0.075
3	0.180	0.237
4	0.008	0.234
5	-0.009	0.092
6	0.025	0.119

### 7.2 Adjustment Factors for the Calculation of Recurrence Probabilities of Multi-Annual Water-Year Rainfall and Run-off Events for the Gladhouse Reservoir Catchment

No. of years (D)	Adjustment factor ( $R_i/D$ )	
	Run-off	Rainfall
2	1.130	1.413
3	1.092	1.294
4	1.068	1.229
5	1.058	1.191
6	1.048	1.166

# APPENDIX 8

## Water Consumption and Population in the East of Scotland in 1971, by Water Board Areas

source : Scottish Development Department (1973)

Water Board	Total conspt. (Ml d <sup>-1</sup> )	Census popn. (1,000's)	% of popn. on public supply	Total conspt. (1 hd <sup>-1</sup> d <sup>-1</sup> )	% of conspt.	
					Domes- tic	Trade
North of Scotland *	28.5	76	96.0	375	82	18
Ross and Cromarty	26.3	59	91.5	446	72	28
Inverness-shire	28.6	89	89.9	321	74	26
North East of Scotland	127.5	434	91.0	335	63	37
East of Scotland	138.0	429	97.1	322	72	28
Fife and Kinross	108.0	328	99.6	329	69	31
Mid-Scotland	203.0	319	99.8	636	43	57
South East of Scotland	273.9	854	99.6	321	66	34

\* includes Orkney and Shetland



APPENDIX 9

An Example of Leaflets Aimed at Reducing Domestic Water  
Consumption in Time of Drought : Produced by the  
South East of Scotland Water Board in 1972

SOUTH-EAST OF SCOTLAND WATER BOARD

# Save Water Now

## Here's How

- RULE 1. Don't Wash Hands under a Running Tap.
- RULE 2. Plug in Basin First.
- RULE 3. Don't Run Cold Water to Waste and wait for Hot Water to Flow.
- RULE 4. When Washing up, collect as many Tea Cups and Dishes as possible so that they can be washed together.
- RULE 5. Don't Wash and Prepare Vegetables under a Running Tap.
- RULE 6. Report all Leaking Taps, Cistern Overflows, Etc. so that they can be repaired immediately.
- RULE 7. Report all Burst Pipes, Water rising in Roads, Leaking Hydrants and Overflows to:—

SOUTH-EAST OF SCOTLAND WATER BOARD

Telephone Number—Office Hours—226 3571

Outwith Office Hours—661 2622

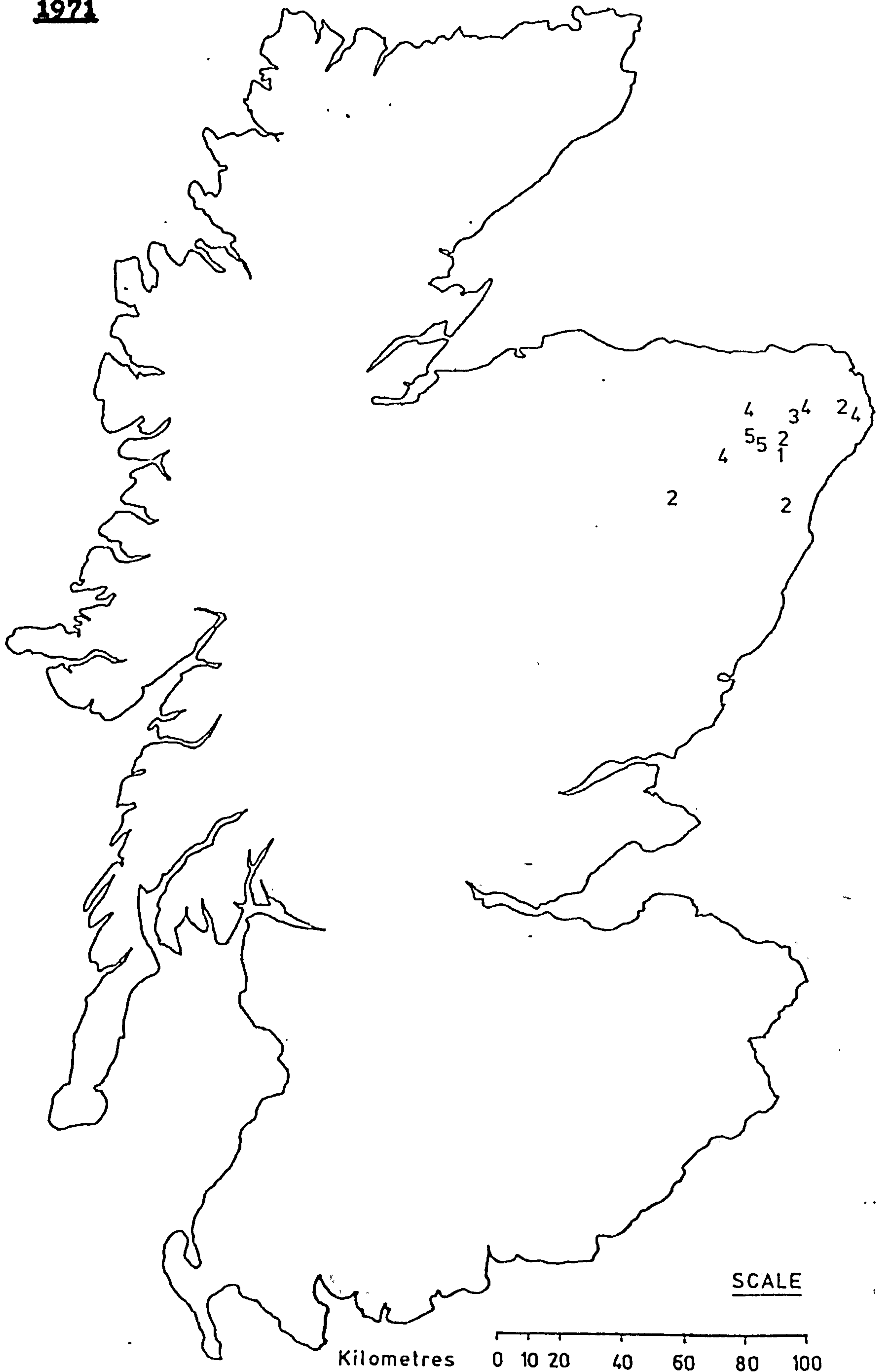
THANK YOU FOR YOUR CO-OPERATION



APPENDIX 10

Transportation of Water Supplies by Road in Scotland  
During the 1971-76 Drought Period : The Number of Months  
of Carting to Given Locations in the Years:

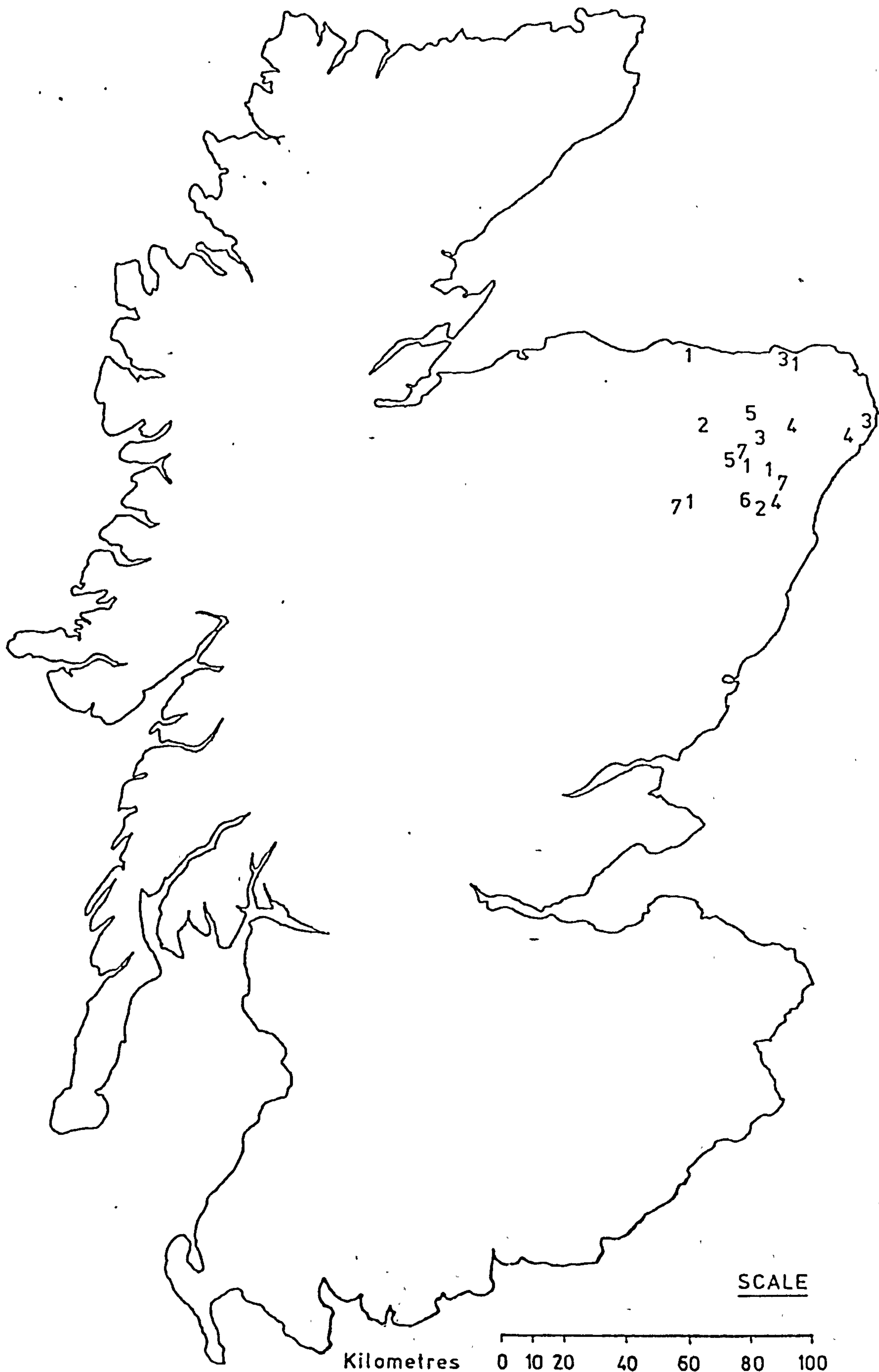
(1) 1971



(2) 1972

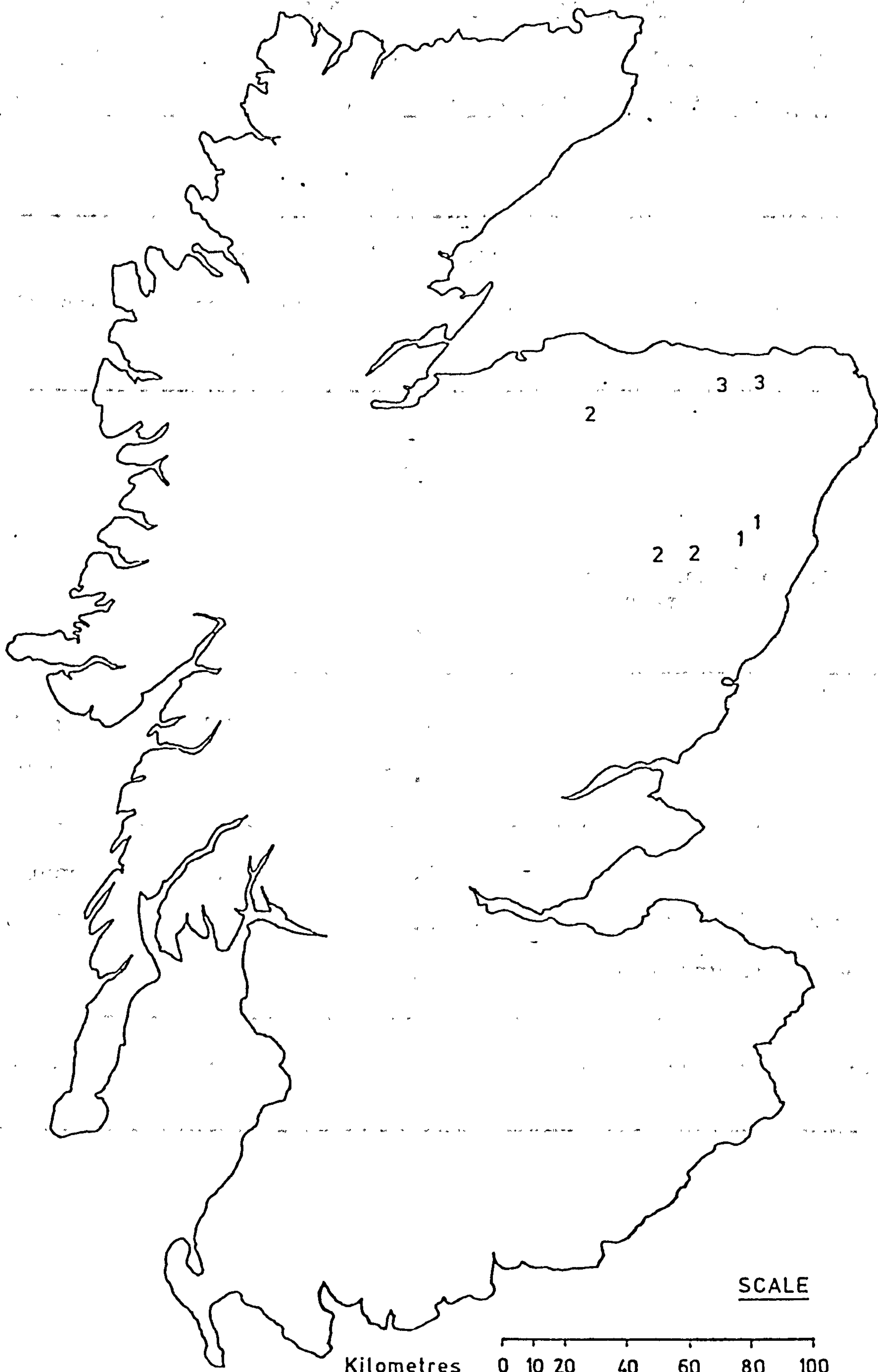


(3) 1973





(4) 1976



# APPENDIX 11

## The Effect on Water Consumption of the Combined Action of Hosepipe Bans and Publicity Campaigns in Given Instances in the East of Scotland During the 1971-76 Drought Period

Supply area	Year of imposition (19__)	Reduction in conspt. (%)	Comments
Fife	71	8.0	very intensive P.R. campaign
	72	8.0	
	73	5.4	
	74	12.8	
	75	4.0	
St. Andrews (in Fife)	72	5.0	
	74	10.0	
Edinburgh and Midlothian	72	5.0	secondary P.R. campaign no hose ban included
	72	3.0	
	74	3.2	
Aberdeen	76	3.5	very little publicity

APPENDIX 12

Steady State Probabilities for Storage States 0 to 9 for  
Gladhouse Reservoir (1885-1976) at Various Levels of Normal  
System Supply (NSS) for:

(1) Summer Minimum Contents

NSS (ML d <sup>-1</sup> )	Storage States and Steady State Probabilities									
	0	1	2	3	4	5	6	7	8	9
27.3	0.012	0.011	0.020	0.034	0.060	0.098	0.150	0.204	0.230	0.181
31.8	0.036	0.027	0.044	0.069	0.102	0.140	0.172	0.181	0.142	0.087
34.6	0.083	0.047	0.067	0.092	0.120	0.145	0.158	0.140	0.097	0.051
37.7	0.192	0.074	0.091	0.108	0.121	0.125	0.115	0.090	0.055	0.029
42.3	0.445	0.093	0.094	0.091	0.084	0.073	0.056	0.037	0.019	0.008

(2) Winter Maximum Contents

NSS (ML d <sup>-1</sup> )	Storage States and Steady State Probabilities									
	0	1	2	3	4	5	6	7	8	9
27.3	0	0	0	0.001	0.002	0.004	0.007	0.012	0.020	0.954
31.8	0	0.001	0.002	0.005	0.009	0.015	0.024	0.036	0.050	0.858
34.6	0.002	0.004	0.008	0.014	0.021	0.032	0.045	0.059	0.073	0.742
37.7	0.010	0.013	0.022	0.034	0.047	0.062	0.075	0.086	0.093	0.558
42.3	0.053	0.044	0.062	0.080	0.095	0.103	0.104	0.099	0.088	0.272



FIG. F.1 RUN-OFF AT THE  
1 PERCENTILE LEVEL  
IN THE  
EAST OF SCOTLAND

An Isometric Illustration  
in units of  $l\ s^{-1}km^{-2}$ , and  
based on the 18 year  
period 1961-78.



Fleming, R.B.  
Ph.D., 1982.  
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SCALE

Kilometres 0 10 20 40 60 80





FIG.F2

RUN-OFF AT THE  
5 PERCENTILE LEVEL  
IN THE  
EAST OF SCOTLAND

An Isometric Illustration  
in units of  $l\ s^{-1}\ km^{-2}$ , and  
based on the 18 year  
period 1961-78.



Penny, R.B.  
Ph.D., 1982.  
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